Journal of Foraminiferal Research, v. 38, no. 4, p. 318–336, October 2008

FORAMINIFERAL TEST ABNORMALITIES IN THE WESTERN BALTIC SEA

Irina Polovodova[1] and Joachim Schönfeld

Leibniz Institute of Marine Sciences IFM-GEOMAR, Wischhofstrasse 1-3, D-24148 Kiel, Germany

ABSTRACT

Abnormal tests were commonly found in recent benthic foraminiferal assemblages in two fjords of the Kiel Bay, the western Baltic Sea. We assessed 18 different types of abnormalities, which were classified into five groups: chamber, apertural, umbilical, coiling and test abnormalities. In both fjords, test abnormalities are over-represented in *Ammonia beccarii* and under-represented in *Elphidium excavatum* subspecies compared to their average proportions in the living assemblages. We found two species-specific abnormality types that occurred only in *Ammonia beccarii*: a bulla-like chamber covering the umbilicus and spiroconvex tests.

In the outer Kiel and Flensburg Fjords, the highest frequencies of abnormal tests were associated with occasional salt-rich, bottom-water inflows from the Belt Sea. Based on the predominance of megalospheric specimens of living foraminifera, it is suggested that coincidence of salinity changes with a reproduction period might be harmful, especially for young individuals, leading to development of abnormal tests. On the other hand, pollution by heavy metals led to higher percentages of abnormal tests in the inner parts of both fjords. Our data show different relationships between abnormal tests and heavy metals in both fjords due to different hydrographical conditions.

Tests of *Ammonia beccarii* found in the Gelting Bay, the Flensburg Fjord, showed traces of dissolution and development of double tests. Such specific abnormal tests mirror the peculiar environmental setting characterized by changes in salinity and enhanced sediment redeposition. It is concluded that abnormal tests as an indicator of environmental pollution have to be used cautiously in areas with strong environmental instability.

INTRODUCTION

A growing number of studies have reported morphological abnormalities of foraminiferal tests from marine (among others, Watkins, 1961; Alve, 1991; Boltovskoy and others, 1991; Sharifi and others, 1991; Yanko and others, 1994, 1998, 1999; Geslin and others, 2002; Bergin and others, 2006) and experimental settings (Mikhalevich, 1976; Wennrich and others, 2007). Deformed foraminiferal tests are considered to come from disruption of the growth plane leading to an abnormal shape in comparison with other specimens of the same species (Murray, 2006). A set of experiments was conducted in order to determine the factors responsible for formation of abnormal tests. Conditions of unfavorable salinity (Stouff and others, 1999 a, b), acidification (Le Cadre and others, 2003), food supply (Murray, 1963), and elevated levels of heavy metals (Sharifi and others, 1991; Saraswat and others, 2004; Le Cadre and Debenay, 2006) were the main factors inducing test abnormalities. In addition, a high proportion of abnormal tests might be induced by intense hydrodynamic conditions (Geslin and others, 2002).

Recently, more attention has been focused on an anthropogenic origin of malformations. Several authors (e.g., Alve, 1991; Sharifi and others, 1991; Yanko and others, 1994, 1998; Samir and El Din, 2001; Bergin and others, 2006; Nigam and others, 2006; Di Leonardo and others, 2007) reported increased frequencies of abnormal foraminiferal tests in estuaries subjected to heavy metal pollution. Moreover, Sharifi and others (1991) and Samir and El Din (2001) showed that deformed tests contained a higher proportion of heavy metals, such as Pb, Zn, Cu, Cr and Cd, than normal ones. Ernst and others (2006) noted the development of abnormal tests in a mesocosm experiment of an oil spill.

Previous studies have described a wide spectrum of malformation types. For instance, Alve (1991) distinguished seven types of morphological deformities: aberrant chamber shape and size, twisted or distorted chamber arrangement, protuberances, multiple apertures, enlarged apertures, reduced chamber size and twinned forms. Yanko and others (1998) distinguished 11 abnormality types of which wrong coiling, poor development of the last whorl, additional chambers, irregular keel, lateral asymmetry and lack of sculpture added to the list of Alve (1991). In addition, over-developed chambers, an excessively high spiral side (spiroconvex tests), a bulla-like chamber covering the umbilicus, an umbilical plug and inflated or deflated tests were reported by Sharifi and others (1991), Samir and El Din (2001), Bergin and others (2006) and Ernst and others (2006) respectively.

Several attempts to classify or systematize abnormal tests have been made. Boltovskoy and Wright (1976) categorized foraminiferal abnormal tests according to their origin: physically (mechanically) or ecologically induced. Yanko and others (1998) subdivided abnormalities into early, intermediate and adult stages, according to the number of whorls and chambers. Stouff and others (1999b) suggested a further distinction, stating that *malformations* are abnormalities that take place during ontogenetic development, whereas *deformities* occur during the life of the adult foraminifer and proposed the term of *morphological abnormalities* when the origin of abnormality is not evident. In the following, we will use the terms deformities and morphological abnormalities.

This study aims to (i) describe the distribution of abnormal tests in the Kiel and Flensburg Fjords of the Kiel Bay; (ii) identify the different types of test abnormality; (iii) classify abnormalities according to morphological criteria and (iv) clarify the factors responsible for the formation of abnormal foraminiferal tests.

[1] Correspondence author. E-mail: ipolovodova@ifm-geomar.de

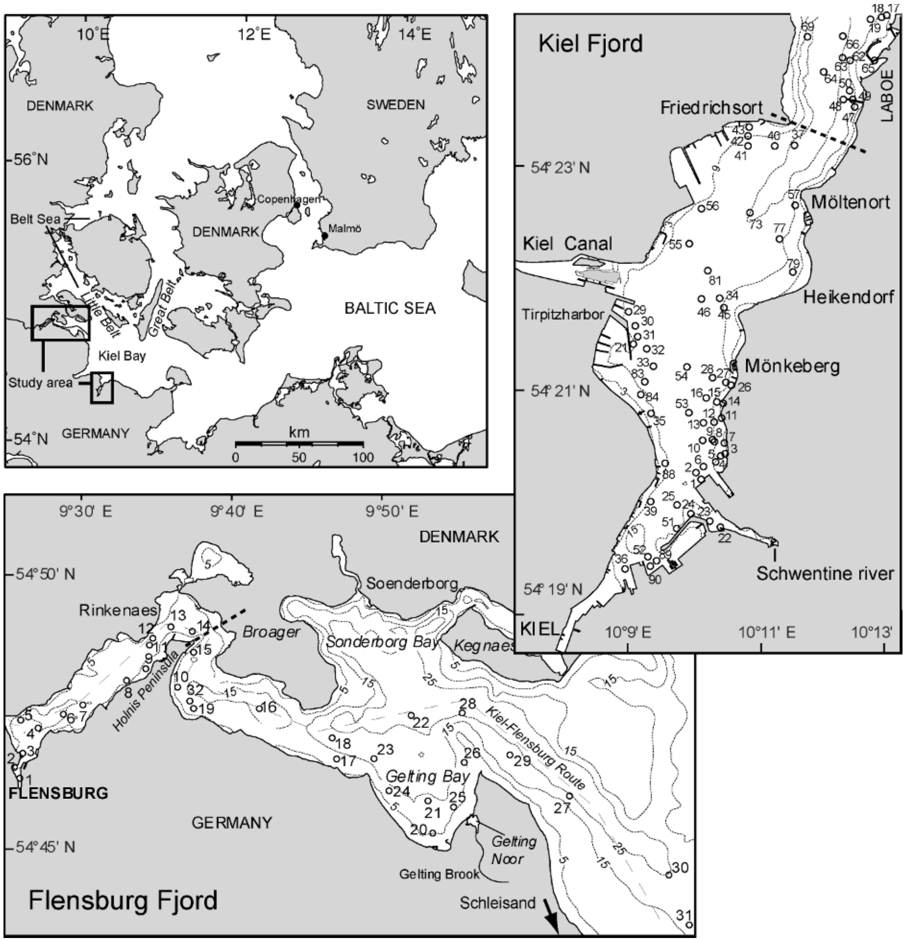

FIGURE 1. Study areas. Black circles indicate the sampling stations. Numbers of stations are given here without prefixes: PF15- for the Kiel Fjord and PF16- for the Flensburg Fjord, for convenience. The stations PF15-20, PF15-38, PF15-60 and PF15-61 are situated far up the outer Kiel Fjord and therefore do not appear on the map. The bold dashed lines indicate a border between inner and outer parts of either fjord.

REGIONAL SETTING

The Kiel Fjord (54°19′–54°30′ N; 10°06′–10°22′ E) is a narrow, 9.5-km-long inlet in the southwestern Baltic Sea (Fig. 1). It comprises two basins: the southern inner fjord (up to 250 m wide) and the northern outer fjord (up to 7.5 km wide), which merges into the Kiel Bay. A network of channel-like depressions connects the inner and outer fjords, beginning in the southern part at 14 m water depth and sloping into the Kiel Bay at approximately 20 m water depth.

Water masses of the Kiel Fjord are similar to those in the Kiel Bay. During summer, the water column is well stratified: surface water of 16°C and average salinity of 14 practical salinity units (psu) overlies deep water of 12°C and up to 21 psu. In winter and spring, the stratification is less pronounced, and water masses of 2°C are uniformly mixed in the inner fjord (Themann, 2002). The influence of occasional salt-rich bottom-water inflows from the Belt Sea, with salinity up to 33 psu, apparently does not play a significant role in the hydrography of the inner Kiel Fjord (Fennel, 1996).

The most important source of sediment to the Kiel Fjord is Pleistocene till, which is eroded from cliffs and shoals in the northwestern part. Shallow coastal areas are characterized by lag sediments with coarse sand and gravel, which grade into sandy muds and silts in depressions. In the innermost fjord, dark, organic-rich muds are encountered even in shallow areas. Foraminiferal tests and shells of other carbonate-producing organisms are subjected to abrasion and corrosion in the sediments. Abrasion and redeposition processes play an important role in the shallow areas of the Kiel Bay, whereas corrosion of foraminiferal tests takes place in the deeper basins due to undersaturation of carbonate in the bottom water (Grobe and Fütterer, 1981).

The Kiel Fjord area is a highly urbanized. The town infrastructure—numerous shipyards, military and sport harbors—and the intensive traffic through the Kiel Canal caused an increase in anthropogenic impact over the last 70 years. In particular, the shipbuilding industry produces substantial heavy metal, oil and TBT (tributyltin) pollution (Helland and Bakke, 2002).

The Flensburg Fjord (53°41′–55°00′ N; 9°24′–10°10′E) is a narrow, 50-km-long, east-west-trending inlet in the northwestern part of the Kiel Bay. The Flensburg Fjord is subdivided into the inner fjord (10–20 m deep; 1.3–3 km wide) and the outer fjord (10–32 m deep; 4 km wide) by the Holnis Haken Shoal, situated off the Holnis Peninsula. The outer Flensburg Fjord comprises the 13–31-m deep Sonderborg Bay, the Gelting Bay (4–22 m deep) and open waters east of the Gelting Peninsula with a high depth range from 5 m in the area of Schleisand to 39 m in the Little Belt. The Gelting Noor is a partly enclosed estuary of the Gelting Brook.

Water exchange with the Kiel Bay is distinctly better in the outer Flensburg Fjord than in the inner part. The Flensburg Fjord is the most protected estuary in the region, and wave action does not reach significant depth, thereby sediment zones are shifted towards shallower waters. During the winter, the inner fjord is well mixed at 6.5°C and a salinity of 21 psu. The water column is well stratified during the summer; surface water averages 17.5°C and 16.5 psu and bottom water is 11°C and 18 psu. Every summer, a stable thermocline develops in the inner fjord at 8–9 m depth (Gemeinsames Komitee Flensburger Förde, 1974). Together with enhanced eutrophication in the 1980's, this setting was responsible for oxygen deficiency that lasted several months without interruption (Wahl, 1985). In the outer fjord, a persistent pycnocline at 16–20 m (Schwarzer and Themann, 2003) separates brackish surface water from salty deep water throughout the year. In the outer fjord, the top of the pycnocline coincides with the effective depth of wave action and divides the sedimentary environments into non-depositional and depositional areas (Exon, 1972).

In general, the sediment distribution in the Flensburg Fjord is similar to that in the Kiel Fjord. Coarse sands prevail in the shallow coastal areas, grading into sandy muds and silt in the deep basins. Dark mud and silt dominate in the inner shallow areas. The Gelting Bay is characterized by sandy sediments, which are predominantly transported from the east by longshore drift (Exon, 1971).

The Flensburg Fjord was strongly exposed to fertilizers and sewage outfalls from the adjacent land in the 1980's. Presently, it is a resort area with a few harbors, yacht traffic and small towns on the shore.

MATERIAL AND METHODS

Surface sediment samples were taken on ten daily cruises of the R/V *Polarfuchs* in the area of the Kiel Fjord between December 2005 and May 2006, and in the Flensburg Fjord in June 2006. The majority of samples was retrieved with a Rumohr corer, which has a sampling tube of 56 mm inner diameter. A van Veen grab was used to recover sandy sediments.

Within minutes after sample retrieval with the Rumohr corer, salinity, temperature and dissolved oxygen content of bottom waters were measured on board with oxygen and conductivity meters (WTW Oxi323/325 and LF320, respectively). The uppermost 1 cm of the sediment was scraped off with a spoon. When sampling with a van Veen grab, cut-off syringes marked with a centimeter scale were used for sampling. Each sample was transferred to a glass vial, homogenized and subsampled for total organic carbon (TOC), total nitrogen (TN), SiO_2, chlorophyll *a* (Chl a) and heavy metals (Cu, Zn, Sn and Pb) analyses. The remaining sediment was transferred to a PVC vial, then preserved and stained with a rose Bengal and ethanol solution (2 g/l; Murray and Bowser, 2000). In total, 77 and 32 samples were taken in the Kiel and Flensburg Fjords respectively (Fig. 1).

The samples were first passed through a 2000-µm screen in order to remove mollusk shells and pebbles, and then they were gently washed with tap water through a sieve with 63-µm openings. These fractions (63–2000 µm and >2000 µm) were dried at 60°C and weighed. The 63–2000-µm fraction was then further split. In order to assess the response of foraminifera to the recent environmental changes reflected in the occurrence of test abnormalities in both fjords, only living foraminifera were studied. All stained foraminifera, considered as living at the time of sampling, were picked from respective aliquots, sorted by species, mounted in Plummer cell slides with glue and counted. Abnormal foraminiferal tests were counted and different types of abnormalities were determined and counted separately. The main types of abnormal tests were photographed using scanning electronic microscopes (SEM), a JSM-6460LV (St. Petersburg State Mining Institute) and a Cam Scan-CS-44 (Institute of Geosciences, Kiel University). Light micrographs of foraminiferal tests were taken with an Olympus MIC-D digital microscope.

To qualitatively estimate the heavy metals within the foraminiferal tests, analyses were made on normal and abnormal tests using an energy dispersive spectrometer (EDS) attached to an SEM (Cam Scan-CS-44). X-ray spectra were obtained at 20 kV accelerating potential and measured in counts (live counting time range 36–77 s). Due to the heterogeneous distribution of trace metals in foraminiferal tests (Severin, 1990), at least three points on each test were measured to check for internal variability of the shell composition. In total, 22 tests were analyzed.

To measure geochemical parameters in sediments, samples were first freeze-dried then powdered in an agate mortar. Measurements of TOC and TN were performed with a Carlo Erba NA-1500-CNS analyzer with accuracy better than $\pm 1.5\%$. Chlorophyll *a* was determined after acetone extraction with a Turner TD-700 Fluorometer with a precision of $\pm 10\%$. Biogenic silica (SiO_2) measurements were done using a Skalar 6000 photometer with a precision of $\pm 1\%$. For heavy metal analyses, the bulk sediment was digested in a mixture of HNO_3, HF, $HClO_4$ and HCl, and measurements of total concentrations of Cu, Zn, Pb and Sn were performed with an AGILENT 7500cs ICP-MS. Blanks and standard MAG-1 were repeatedly analyzed together with the samples in order to evaluate the precision and accuracy of the measurements. The accuracy of analytical results as estimated from replicate standard measurements was better than $\pm 1.5\%$.

A detailed review of sediment geochemistry, including analytical methods, can be found in Nikulina and others (2007). Results of geochemical characteristics of surface sediments in the Flensburg Fjord will be given elsewhere. For correlation of geochemical parameters and foraminiferal data, Pearson's correlation coefficient was used. Statistical analysis was performed by means of the software package, STATISTICA 6.0.

RESULTS

Hydrography

Since our sampling campaign in the Kiel Fjord comprised several seasons, the temperature and salinity of near-bottom water showed a pronounced seasonality.

Temperature decreased from 8°C on average in December 2005 to 2°C in February, and raised again to 7°C in May 2006. In December 2005, the near-bottom water showed the highest salinity with 23.2 psu and minimum values of 16.5 psu in May. In the Schwentine river mouth, the boundary layer between riverine fresh water and saline fjord water was encountered at approximately 1 m depth in February.

The oxygen concentration mostly exceeded 400 μmol/l and decreased slightly only in the deep basins. The saturation levels varied from 58% to 100%. As such, a true oxygen deficiency in the near-bottom waters of Kiel Fjord was not recognized.

In the Flensburg Fjord, temperature and salinity of near-bottom water ranged from 7.2–13.7°C and 18.3–25.4 psu, respectively, in June 2006. The lowest temperature and highest salinity were encountered in depressions of the inner and outer parts. The highest temperature in the Flensburg Fjord was observed in the southernmost Gelting Bay. Two stations in the Gelting Bay (PF15-20 and PF15-26) had the lowest salinity values (18.3 and 18.9 psu), which reflect, apparently, the influence of the Gelting Brook, bringing freshwater to this area.

The content of dissolved oxygen in near-bottom water of the Flensburg Fjord was lower than that in the Kiel Fjord and ranged from 160–308 μmol/l, with the highest value off the Gelting Noor. The saturation levels varied from 48–100%, clearly not oxygen deficient.

Definition of Abnormality Types

Seventeen types of aberrant foraminiferal tests were recognized in the Kiel Fjord and 15 types in the Flensburg Fjord. All abnormal tests were divided into five groups.

1) *Chamber abnormalities* include aberrant chamber shape (Pl. 1, Fig. 6); twisted chamber arrangement; additional chambers (Pl. 1, Figs. 5, 8); reduced chamber size (Pl. 1, Figs. 4, 13, 22; Pl. 2, Fig. 14); overdeveloped chambers of the last whorl (Pl. 1, Fig. 14, 21) and protuberances. Protuberances and abnormally protruding chambers were previously described by Alve (1991), Almogi-Labin and others (1992), Yanko and others (1994), Geslin and others (2000, 2002). Identification of the latter two abnormalities is a challenging task, because they can be confused with the frustrated double tests (Stouff and others, 1999a). During the early ontogenetic stage, two second chambers can grow from one proloculus with subsequent development of an independent whorl from each of the second chambers. If only one whorl develops from one of these chambers, then the other appears as a protuberance on the proloculus (Stouff and others, 1999a; Pl. 2, Fig. 4).
2) *Apertural abnormalities* consist of multiple apertures on tests (Pl. 1, Fig. 15; Pl. 2, Fig. 12).
3) *Abnormalities of the umbilical side* of the test include a bulla-like chamber covering the umbilicus. This feature was previously described by Frontalini and Coccioni (2008; Pl. 2, Fig. 9) as an abnormally protruding chamber, whereas Bergin and others (2006) reported it as umbilical plug. Unfortunately, the latter did not provide images of their abnormal tests. As such, we can only suggest that the abnormal umbilical plug, mentioned by Bergin and others (2006), differs from the normal plug of schizont test morphology, reported by Stouff and others (1999c).
4) *Abnormal coiling* includes a wrong direction of coiling, poor development of the last whorl (Pl. 1, Fig. 24), and development of several whorls with different axes of rotation (Pl. 1, Fig. 16; Pl. 2, Figs. 7a,b, 8, 13).
5) *Test abnormalities* comprise several structures including an irregular keel, twinning (Pl. 1, Fig. 9; Pl. 2, Fig. 4), lack of sculpture (Pl. 1, Fig. 12), an excessively high spiral side or spiroconvex tests (Pl. 1, Fig. 7), twisting of entire test (Pl. 2, Figs. 9, 15), compressed tests (Pl. 1, Fig. 19; Pl. 2, Fig. 3) and non-developed tests. The latter represent tests with smoothed ornamentation, but with distinguishable chambers, as compared to the tests that lack sculpture.

Some tests had multiple apertures and several whorls with different axes of rotation. It is likely that those correspond to the double and multiple tests of Stouff and others (1999a), and to those described by some authors as twinned tests (Alve, 1991; Sharifi and others, 1991; Yanko and others, 1998).

Kiel Fjord

Distribution of Abnormal Tests

The living benthic foraminiferal fauna in the Kiel Fjord includes nine species, among which *Ammonia beccarii* (52% of all specimens on average) and subspecies of *Elphidium excavatum* (44% on average) are dominant (Appendix 4). *Elphidium incertum*, *E. gerthi*, *E. albiumbilicatum*, *E. williamsoni*, *E. guntheri*, *Ammotium cassis and Reophax dentaliniformis* are rare (less than 3%).

The morphological abnormalities were encountered in six species (Table 1). The majority of abnormal tests was found in *Ammonia beccarii*, which has 73% of all the abnormal tests observed in living specimens in this area. Less abundant were abnormalities in *Elphidium excavatum excavatum* (16%), *E. excavatum clavatum* (4%), *E. gerthi* (3%), *E. incertum* (3%) and *E. albiumbilicatum* (1%). It is evident from the percentages that abnormalities are over-represented in *A. beccarii* and under-represented in *E. excavatum* subspecies compared to their average proportions in the living assemblages of the Kiel Fjord.

The percentage of abnormal tests recorded in samples collected in the Kiel Fjord range between 0–25%. Abnormality frequencies higher than 10% were found in 10 of 77 samples. High proportions of abnormal tests occurred in samples from marginal sites (Fig. 2) to the north offshore from the Laboe resort (PF15-17; 25%) and in the coastal zone near Heikendorf (17%). A transect consisting of four stations (PF15-22–PF15-25) taken from the inner part of Schwentine river through its estuary to the western shore of the fjord had higher percentages of abnormal tests close to the river mouth (15%) compared to the western side (11%). Relatively high proportions of abnormal tests were also detected near the Tirpitz Harbor (13%), which is used by the military, near a former oil pier (12%) in Mönkeberg,

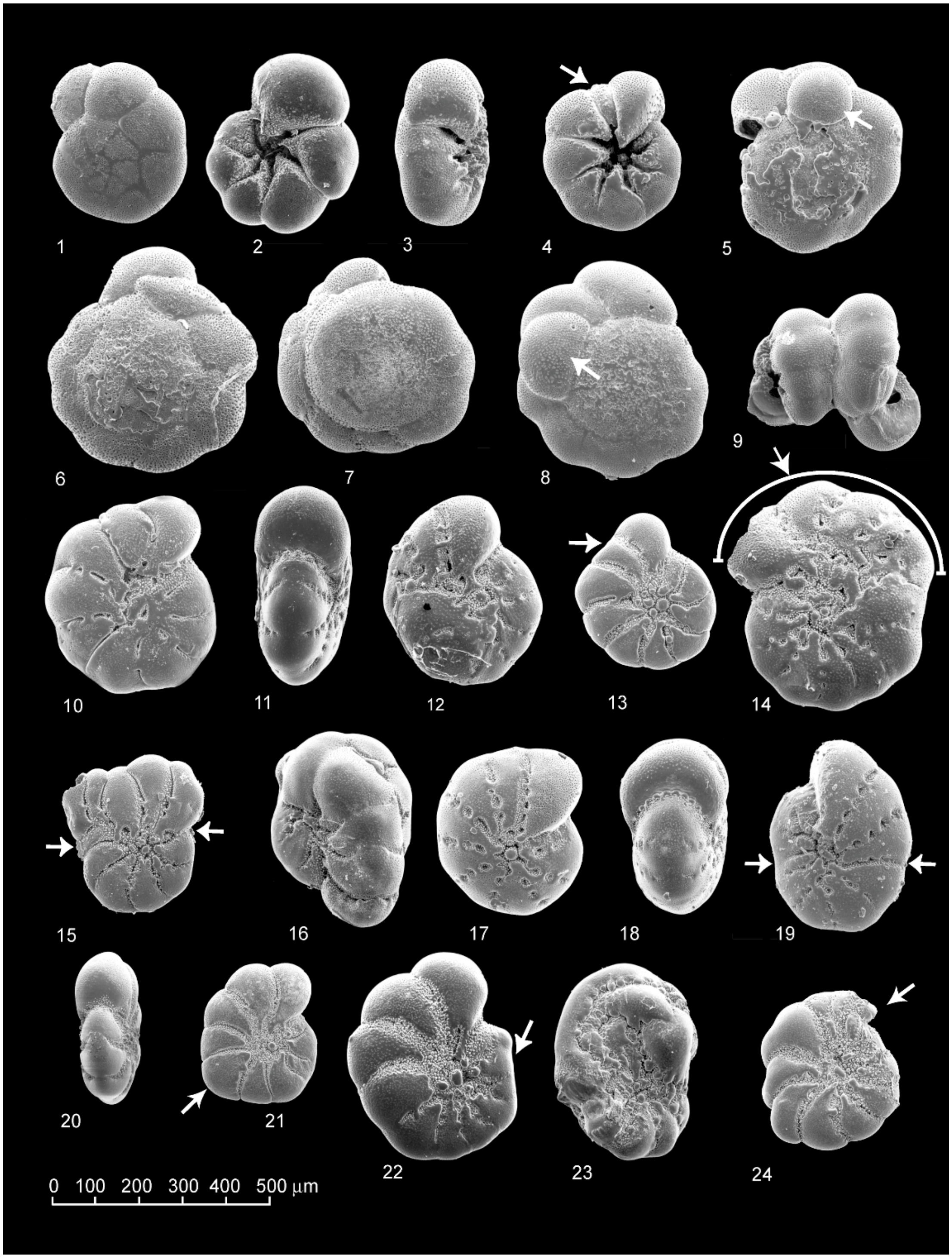

PLATE 1

Normal and abnormal specimens encountered in the Kiel Fjord. **1–9** *Ammonia beccarii*: **1–3** Spiral, umbilical and apertural views of a normal specimen; **4** Abnormal test with reduced chamber size (arrow); **5, 8** Additional chambers on the spiral side of the test; **5** Note the regeneration scars at the basement of an additional chamber (arrow); **6** Aberrant shape of the last chambers; **7** Excessively spiroconvex test with a distinctly high spiral side; **9** The double test (twins) showing the fusion of two specimens of the same size by spiral sides. **10–16** *Elphidium excavatum excavatum*: **10–11** Spiral and apertural views of a normal specimen; **12** Abnormal test with a lack of sculpture at the spiral side; **13** Reduced chamber size (arrow); **14** Overdeveloped chambers of the last whorl; **15** Double apertures (arrows); **16** Abnormal test exhibiting the development of several whorls with different axes of rotation. **17–19** *Elphidium excavatum clavatum*: **17–18** Spiral and apertural view of a normal specimen; **19** Compressed test (arrows). **20–24** *Elphidium gerthi*: **20** Apertural view of a normal specimen; **21** Abnormal test possessing a slightly overdeveloped chamber (arrow); **22** Reduced chamber size (arrow); **23** Abnormal specimen with a complex form of abnormality leading to difficulties with its taxonomical identification as *E. gerthi*; **24** Poor development of the last whorl.

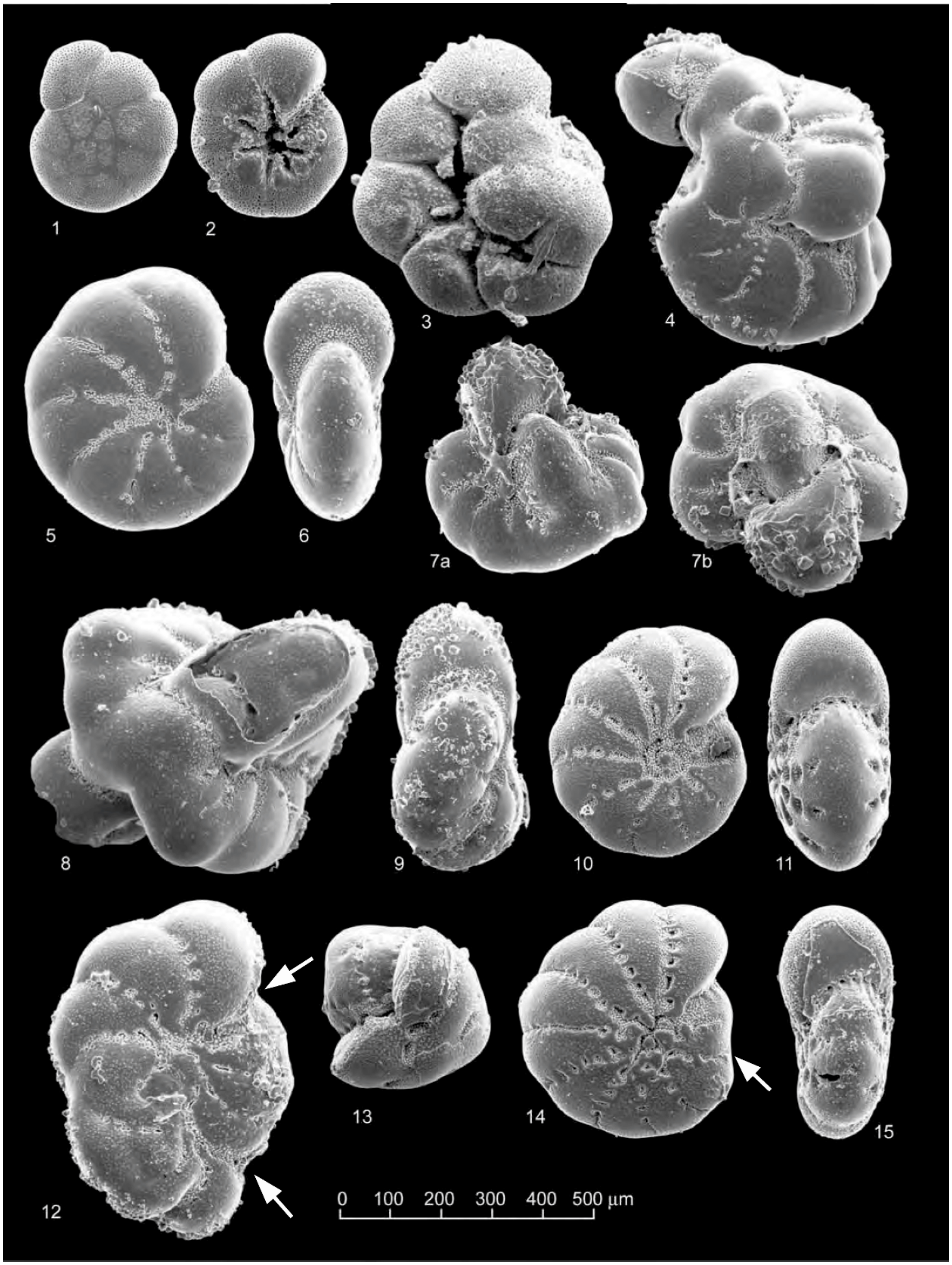

PLATE 2

Normal and abnormal specimens observed in the Flensburg Fjord. **1–3** *Ammonia beccarii*: **1–2** Spiral and umbilical views of normal specimen; **3** Compressed test, umbilical view. **4–9, 12** *Elphidium incertum*: **4** Double test; **5, 6** Spiral and apertural views of a normal specimen; **7a, 7b, 8** Development of two whorls with different axes of rotation; **9** Twisting of entire test; **12** Abnormal test with double apertures (arrows). **13** Apertural view of an *Elphidium* sp. having two whorls with different axes of rotation. **10, 11, 14, 15** *Elphidium excavatum excavatum*: **10, 11** Spiral and apertural views of a normal specimen; **14** Abnormal test with reduced chamber size (arrow); **15** Twisting of entire test.

TABLE 1. Counts of the different types of test abnormality observed in foraminiferal species of the Kiel Fjord.

Foraminiferal species	Morphological abnormalities	Chamber abnormalities: Aberrant chamber shape	Chamber abnormalities: Twisted and distorted chamber arrangement	Chamber abnormalities: Additional chamber	Chamber abnormalities: Reduced size of chambers	Chamber abnormalities: Overdeveloped chambers	Chamber abnormalities: Protuberances	ApA*: Multiple apertures	Abnormal coiling: Wrong coiling	Abnormal coiling: Poor development of the last whorl	Abnormal coiling: Development of two independent whorls	Test abnormalities: Twinning	Test abnormalities: Lack of sculpture	Test abnormalities: Spiroconvex tests	Test abnormalities: Compressed tests	Test abnormalities: Twisting of the entire test	Test abnormalities: Non-developed test	Test abnormalities: Complex form	UmA*: Bulla-like chamber at the umbilicus	Total number of abnormal tests	Species proportion of all abnormalities (%)	Average proportion in all samples (%)
Ammonia beccarii		103	29	12	120	76	26	2	22	1	1	7	1	75	45	14	2	5	2	543	73	66
Elphidium exc. excavatum		24	7	5	43	1	6	1	3	1	2	2			20	3	2	1		121	16	31
Elphidium exc. clavatum		2			14	2	1		1		3				5					28	4	28
Elphidium gerthi		3	1	3	11							1			3					22	3	17
Elphidium incertum		3			6	3	2	1	3		2	2			2					24	3	29
Elphidium albiumbilicatum				1	1	3														5	1	12

* ApA and UmA indicate apertural and umbilical abnormalities, respectively

and in the central and northwestern parts of the inner fjord (10%). Stations PF15-20, PF15-60 and PF15-61 in the outer Kiel Fjord showed relatively low proportions of abnormal tests (4% on average).

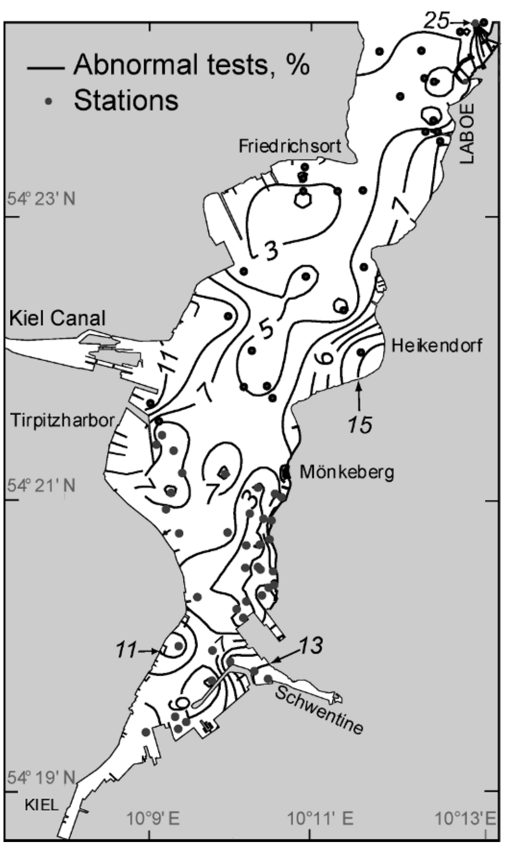

FIGURE 2. Spatial distribution of the total abnormalities among foraminifera in the Kiel Fjord.

Diversity of Abnormal Tests

The maximum variety of test abnormalities was seen in the most abundant taxa, *Ammonia beccarii* and *Elphidium excavatum* subspecies. Only three types of deformities were observed in *E. albiumbilicatum*, which inhabits an area with strong currents in the Kiel Fjord (Nikulina and others, 2007).

Specimens of *Ammonia beccarii* showed the next most dominant abnormalities: reduced size of chambers (22% of all abnormalities in this species), aberrant chamber shape (19%), overdeveloped chambers (14%), excessively spiroconvex tests (14%) and compressed tests (8%). The prevailing abnormalities of *Elphidium excavatum excavatum* were reduced chamber size (36%), aberrant chamber shape (20%) and compressed tests (17%). Fifty percent of the abnormal tests of *E. excavatum clavatum* had reduced chambers, 18% were compressed and 10% showed the development of two whorls with different axes of rotation. Reduced chamber size prevailed also in *E. incertum* and *E. gerthi* (Table 1). Only five abnormal tests of *E. albiumbilicatum* were found, and three of them showed overdeveloped chambers. It comes out that, with the exception of *E. albiumbilicatum*, all *Elphidium* species have a similar diversity of abnormality types.

The lack of sculpture and the occurrence of a bulla-like chamber covering the umbilicus were rare in the Kiel Fjord. However, a bulla-like chamber and excessively spiroconvex tests are common only to *Ammonia beccarii*, due to its low trochospiral test morphology.

Heavily deformed foraminiferal tests were also encountered mainly in *Ammonia beccarii*. These tests showed several types of abnormality, sometimes making their taxonomic identification difficult (Pl. 1, Fig. 23). We considered such tests as a complex form of test abnormalities (Table 1).

In order to show the spatial distribution of the five abnormality groups in both fjords, we created a map

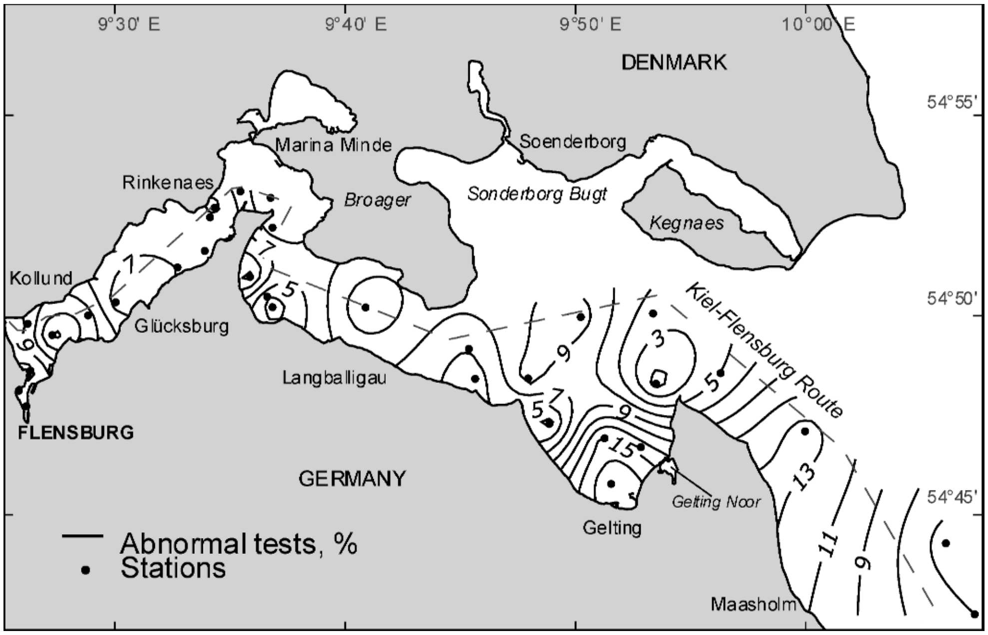

FIGURE 3. Spatial distribution of the total abnormalities among foraminifera in the Flensburg Fjord.

(Fig. 4), based on absolute counts of abnormal tests per sample volume (10 cc). It showed that in the Kiel Fjord, chamber abnormalities dominated outside the Kiel Canal, in the inner fjord, and in the northern fjord. Test abnormalities were frequent near the Schwentine river mouth, along the eastern shore of the fjord, near the Tirpitzharbor and in the outer fjord. Tests with abnormal coiling were abundant in the inner Kiel Fjord, but apertural abnormalities were rare in the Kiel Fjord, occurring more frequently in the outer fjord. Isolated specimens with umbilical abnormalities occurred near the Schwentine river mouth.

FLENSBURG FJORD

Distribution of Abnormal Tests

The living benthic foraminiferal assemblages in the Flensburg Fjord are dominated by *Elphidium excavatum* subspecies (37% on average), *E. incertum* (28% on average) and *Ammonia beccarii* (25% on average). *Elphidium albiumbilicatum* is common (10% on average), whereas *Reophax dentaliniformis regularis*, *Ammotium cassis*, *Elphidium gerthi* and *E. williamsoni* are rare (1% on average).

The proportion of specimens with aberrant tests varies between 0–19% in the Flensburg Fjord. Most of the abnormal individuals come from the dominant species: *Ammonia beccarii*, *Elphidium incertum* and *E. excavatum* subspecies (representing 40, 32 and 25% of all deformed tests, respectively). This shows again that tests abnormalities are over-represented in *A. beccarii* (with reference to the average proportion of this species in the living assemblages of the Flensburg Fjord).

The highest proportion of abnormal specimens (19%) was recorded in the Gelting Bay (Fig. 3). Furthermore, we observed high abundances of abnormalities in the innermost (PF16-04) and outer (PF16-10 and PF16-27) fjords. More than 10% of abnormal tests were seen at four stations that are situated along the shipping lane, the Kiel-Flensburg Route (Fig. 3). Low percentages of abnormalities were encountered in the eastern Gelting Bay (3%) and at station PF16-19 (1.8%) in the outer fjord.

Diversity of Abnormal Tests

The highest variety of abnormalities in the Flensburg Fjord was observed in *Ammonia beccarii* and *Elphidium incertum*, which respectively showed twelve and eleven abnormality types (Table 2). Ten and five different types of abnormalities were observed in the tests of *Elphidium excavatum* subspecies and *E. albiumbilicatum*, respectively.

Ammonia beccarii showed excessively spiroconvex tests (26%), reduced chambers (22%) and aberrant chamber shape (16%) as dominant abnormalities. Most of abnormal tests in *Elphidium excavatum excavatum* had reduced chambers (39%). The latter abnormality prevailed also in *Elphidium excavatum clavatum* (36%), *E. albiumbilicatum* (five of ten tests) and *E. incertum* (25%). These species also showed aberrant chamber shape (22%) as a common type of abnormal tests. Thus, the distribution of the abnormality types in *A. beccarii* is different between the Flensburg Fjord and the Kiel Fjord, whereas *Elphidium* species showed similar abnormal test types between these areas.

Multiple apertures, irregular keel and poor development of the last whorl are rare types of foraminiferal test abnormalities in the Flensburg Fjord. Only two tests exhibiting several types of abnormality were found in *Ammonia beccarii* and *Elphidium incertum*.

In the eastern Gelting Bay, near the Gelting Noor, we found specimens of *Ammonia beccarii* with unusually thin or opaque shell walls (Pl. 4, Figs. 2, 3) and extremely corroded tests (Pl. 3, Figs. 4, 5). In some cases, only the inner organic lining was left (Pl. 3, Fig. 6). Some of these specimens also showed a distinct type of abnormality, where a small, deformed foraminifer was firmly attached to

TABLE 2. Counts of the different types of test abnormality observed in foraminiferal species of the Flensburg Fjord.

		Chamber abnormalities						ApA*	Abnormal coiling			Test abnormalities						UmA*			
Foraminiferal species	Morphological abnormalities	Abberrant chamber shape	Twisted and distorted chamber arrangement	Additional chamber	Reduced size of chambers	Overdeveloped chambers	Protuberances	Multiple apertures	Wrong coiling	Poor development of the last whorl	Development of two different whorls	Irregular keel	Twinning	Spiroconvex tests	Compressed tests	Twisting of the entire test	Complex form	Bulla-like chamber at the umbilicus	Total number of deformed tests	Species proportion of all abnormalities (%)	Average proportion in all samples (%)
Ammonia beccarii		23	1		31	13	7		11		1		4	37	7	6	1	2	144	40	56
Elphidium excavatum excavatum		9		1	22	9	2		2	1		1	2		7				56	15	36
Elphidium excavatum clavatum		9		1	13	1	1	1	2		1				5	2			36	10	27
Elphidium gerthi		1																	1	0.3	7
Elphidium incertum		26	1	8	29	19	6		10		2		5		9	1	1		117	32	44
Elphidium albiumbilicatum		2		1	5				1						1				10	3	14

* ApA and UmA indicate apertural and umbilical abnormalities, respectively.

a bigger corroded or destroyed test (Pl. 4, Figs. 4, 9). The chambers of the smaller specimen were deformed, more tightly arranged, and had extremely thin walls. Samples taken in the southern and central Gelting Bay also contain tests of *A. beccarii* with slight traces of corrosion or dissolution. All corroded specimens of *A. beccarii* in the Gelting Bay showed a bright rose-Bengal staining and were considered alive when sampled.

A map of the spatial distribution of the five abnormality groups (Fig. 4b) in the Flensburg Fjord showed that chamber abnormalities were concentrated in the outer fjord, the southernmost Gelting Bay and the innermost part of the fjord. Test abnormalities showed the highest frequencies in the Gelting Bay and the outer fjord. Tests with abnormal coiling had a uniform distribution, though the highest amount was linked to the outer fjord. Apertural abnormalities occurred rarely in Flensburg Fjord and tended to occur most frequently the outer fjord. Isolated tests with umbilical abnormalities occurred in the Gelting Bay.

Distribution of Abnormalities Between Living and Dead Assemblages

To test fossil assemblages for abnormal tests, we analyzed the total foraminiferal fauna in one unstained control sample, taken in the outer Kiel Fjord in 2007 at the same location, where sample PF15-38 was taken. As a result, we observed that 26% of the foraminiferal tests were abnormal in the uppermost centimeter of sediments, which comprises approximately 10 years. Keeping in mind the value of 4% observed among living specimens at station PF15-38, we can assess how many abnormal specimens were present in the dead fauna (22%). A distinct difference (18%) in abnormalities between living and dead assemblages indicates that elevated frequencies of abnormal tests are a phenomenon that takes place not only recently, but also during the past decade, when environmental stress and anthropogenic pollution were high in the Kiel Fjord.

The distribution of abnormalities between different species in the dead assemblage was similar to that in the living fauna. In both cases, abnormal specimens were overrepresented in *Elphidium excavatum* subspecies. We also found a predominance of reduced (44%) and overdeveloped chambers (33%) in the dead assemblage. Reduced chamber size (29%) was one of the most abundant abnormality types in the living fauna, together with aberrant shape (43%) and twisted arrangement (29%) of the chambers.

Test Abnormalities and Sediment Geochemistry

In order to determine the response of benthic foraminifera to recent human-induced stress in the Kiel and Flensburg Fjords, surface sediment samples were analyzed for a set of trace metals: Cu, Sn, Zn and Pb, which are associated with the shipbuilding industry. Copper, tin and zinc have been used as biocides in antifouling paints (Bellinger and Benham, 1978; Clark and others, 1988; Helland and Bakke, 2002), whereas lead is known to come from boat and ship exhaust systems (Abu-Hilal and Badran, 1990) and also forms the pigment base of anticorrosives and primer paints (V.-Balogh, 1988).

In Kiel Fjord, we found among living specimens at station PF15-79 off Heikendorf higher proportions of abnormal tests (17%) with an exceptionally high lead content (2169 mg/kg), which is two orders of magnitude higher than 20 mg/kg, an average lead concentration known for nearshore muds (Chester and Aston, 1976). Likewise, a relatively high percentage of abnormalities

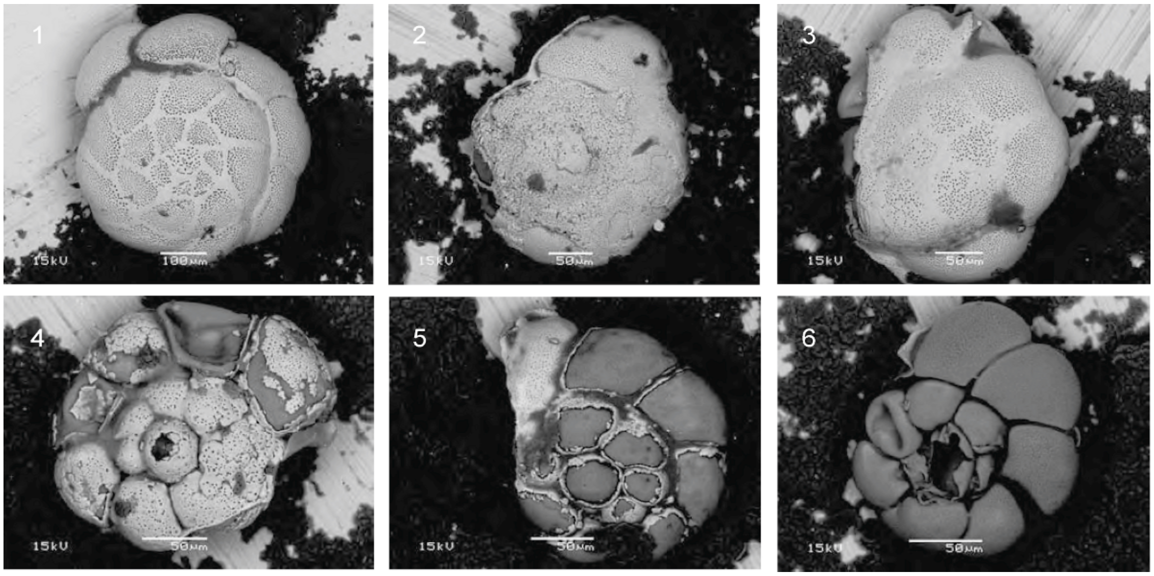

PLATE 3

Different stages of test dissolution observed in tests of *Ammonia beccarii* from the Gelting Bay, the Flensburg Fjord: **1** Normal test; **2** Loss of last chambers, which are thinner (note the initial dissolution process taking place on the spiral side of the test); **3** Loss of last chambers, which are thinner (note that the organic lining is visible at the place where a last chamber dissolved); **4** Dissolution of the following chambers; **5** Heavily dissolved test with interlocular walls remaining (star-shaped form); **6** Elastic organic lining folded in places. Scale bar – 100 and 50 µm (**1** and **2–6**, respectively). Images are taken with a JSM-6460LV SEM without coating.

(10%) in the central part of the fjord coincides with the high level of Sn (15 mg/kg), which is seven times higher than 2 mg/kg, an average concentration of tin found in nearshore muds (Wedepohl, 1960). In spite of this, no significant correlations between the total proportion of abnormal tests and content of heavy metals in the sediments were recognized in either fjord, (Fig. 5a, b). However, the limited number of samples where certain abnormalities were found and where heavy metals were measured impeded a precise determination of the relationships between different types of abnormality and environmental parameters. Though the proportion of tests with additional chambers (var = 121.36) in Kiel Fjord correlated negatively with sedimentary Sn ($r = -0.501$), this relationship failed the Student's *t-test* for significance (Table 3, Fig. 5c). On the other hand, the occurrence of tests with a wrong coiling showed significant negative correlations with TOC, TN and Chl a ($r = -0.522$, -0.578, -0.763, respectively).

In the Flensburg Fjord, counts of tests with additional chambers and twisted tests were available together with content of heavy metals in only five samples (Fig. 5d). These samples showed significant positive correlations between the proportions of tests with additional chambers and Cu ($r = 0.886$), Zn ($r = 0.857$), Sn ($r = 0.831$) and Pb ($r = 0.847$) content in sediments. A negative correlation of this abnormality with TN was also found, and twisting of the entire test (var = 18,544) correlated positively with all the heavy metals measured (Table 3). However, these latter two relationships failed the significance test. In addition, EDS analysis did not reveal high concentrations of heavy metals in abnormal tests as compared to normal ones from either fjord (Fig. 6).

DISCUSSION

Abnormal Tests as Indicators of Heavy Metal Pollution?

The presence of abnormal tests in benthic foraminiferal communities was reported from various types of environments, in particular those polluted by heavy metals (Alve, 1991; Sharifi and others, 1991; Yanko and others, 1994, 1998, 1999; Samir and El Din, 2001; Geslin and others, 2002; Bergin and others, 2006; Burone and others, 2006; Di Leonardo and others, 2007; Frontalini and Coccioni, 2008; among others). It is important to determine the percentage of abnormal tests typical of normal environments in order to compare with percentages in polluted environments. Alve (1991) found 1% abnormal foraminiferal tests in unstressed foraminiferal assemblages. The same value was also obtained in laboratory experiments (Stouff and others, 1999b).

In Kiel Fjord, we observed high abnormalities at station PF15-79 and in the central fjord in sediments highly enriched in lead (>100 mg/kg) and tin (>10 mg/kg), respectively. The extraordinarily high level of Pb (>2000 mg/kg) at station PF15-79 and other high values are regarded with caution because no measurements were replicated. Nonetheless, coal and ash residues, which were commonly found in sediments of the Kiel Fjord, can contribute to high lead and tin concentrations (Erlenkeuser and others, 1974; Reeder and others, 2006). On the other hand, the Kiel Fjord was a strategic target during the Second World War (RIIA, 1990), and it well might be that corrosion of old ammunition buried in the vicinity of the sampling site led to high metal concentrations. In addition, the muddy sediments at station PF15-79 suggest an active

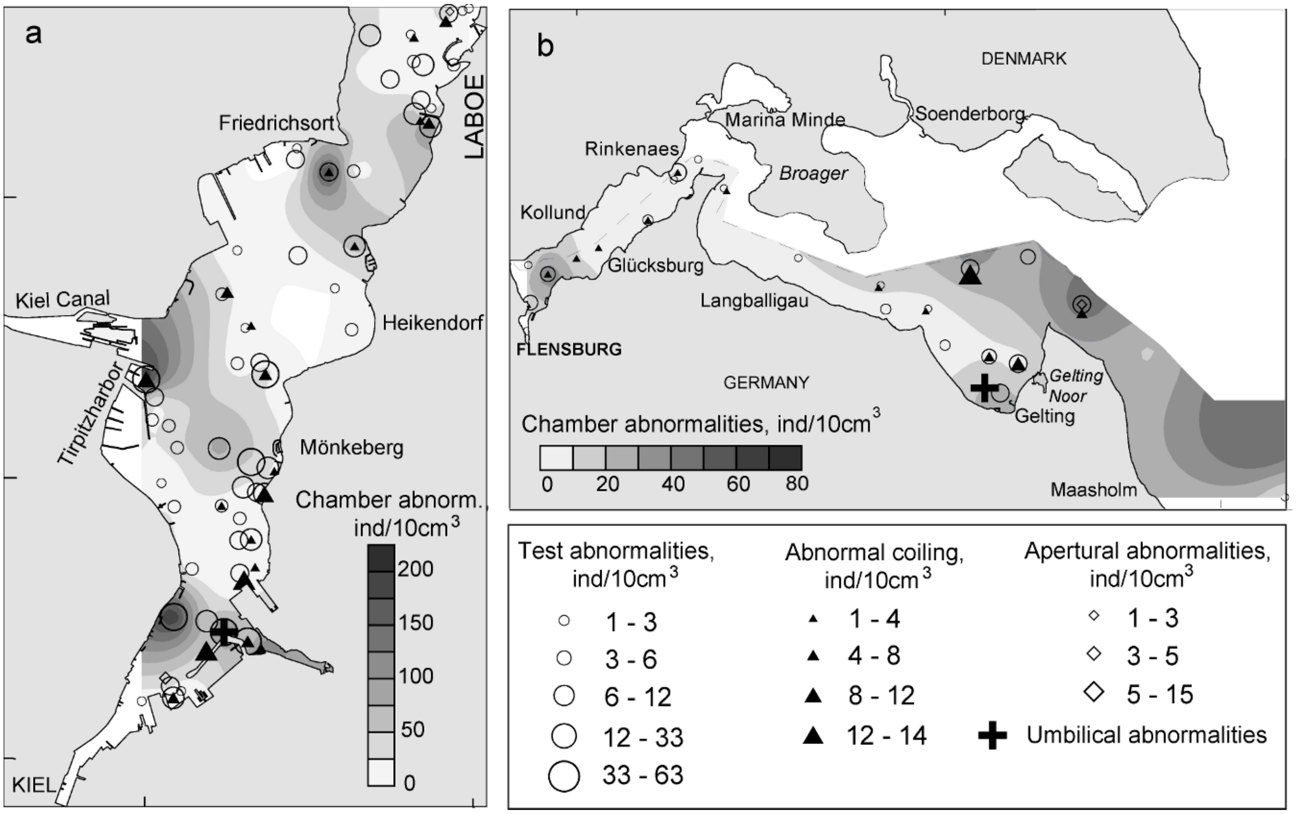

FIGURE 4. Map showing the spatial distribution of the five groups of test abnormalities in **a** the Kiel Fjord and **b** the Flensburg Fjord. Note that units in the legend represent the absolute counts of abnormal individuals standardized per sample volume (ind./10 cc). Legend in the frame is given for both fjords.

depositional center, which also could explain the high levels of lead and tin.

Muddy sediments and organic matter form substrates that adsorb heavy metals (Tessier and Campbell, 1987) and, therefore, affect metal speciation, mobility and bioavailability in sediments. The most bioavailable are oxides and carbonates of lead (Reeder and others, 2006). Unfortunately, we did not do selective chemical extraction of heavy metals from sediments and therefore can only speculate about their speciation and bioavailability to foraminifera. Ankley and others (1994) discussed the role of iron sulfide complexes in reducing the bioavailability of lead in sediments and pore waters. They noted seasonality in concentrations of these complexes in surface sediments with a minimum in winter and a maximum in late spring - early summer. However, sample PF15-79 was taken in the Kiel Fjord at the beginning of May, when concentrations of iron sulfides were supposed to be high making lead unavailable to foraminifera. Apparently, some other factors are responsible for elevated foraminiferal abnormalities off Heikendorf.

In turn, the positive correlations of tests with additional chambers to Cu, Pb, Sn and Zn in the Flensburg Fjord confirm the harmful influence of pollutants. However, one should keep in mind that a small sample size (n=5) makes these results debatable. Nevertheless, tests with additional chambers are abundantly found in the inner Flensburg Fjord where muddy sediments and the highest levels of heavy metals were encountered (Fig. 5d). On the other hand, every year, sediments of the inner Flensburg Fjord are exposed to seasonal oxygen deficiency (Wahl, 1985; LANU, 2007). This provides suitable conditions for the formation of iron sulfide complexes, an important binding phase for metals, in contrast to aerobic sediments, in which iron sulfides are readily oxidized (Ankley and others, 1994). Thus, during changes from reducing to oxidizing conditions, heavy metals can become bioavailable (Förstner, 1993; Siegel, 2002; Alloway, 2005), explaining, therefore, a positive relationship between additional chambers and heavy metals in sediments of the Flensburg Fjord.

Such surprisingly different relationships between tests with additional chambers and Sn content in the sediments of the Kiel and Flensburg fjords (Fig. 5c, d) raise a question about the possible reasons. It is evident from our observations and hydrographic data that salinity, on average, is higher in the Flensburg Fjord than in the Kiel Fjord. As such, it could well be that the bioavailability of tin to foraminifera is higher in the Flensburg Fjord than in the Kiel Fjord, due to different physico-chemical conditions: higher salinity and therefore a more alkaline pH. With the exception of copper and mercury, there is a rapid decrease in the proportion of heavy metals bound to organic matter as the salinity increases (Mantoura and others, 1978; Siegel, 2002). This is mainly due to a competition for the humic ligands with calcium and magnesium, which are highly abundant in seawater. Rüdel (2003) reported an increased bioavailability of organotin compounds at more alkaline pH values. Taking into account that toxicity of metallic and inorganic tin is low

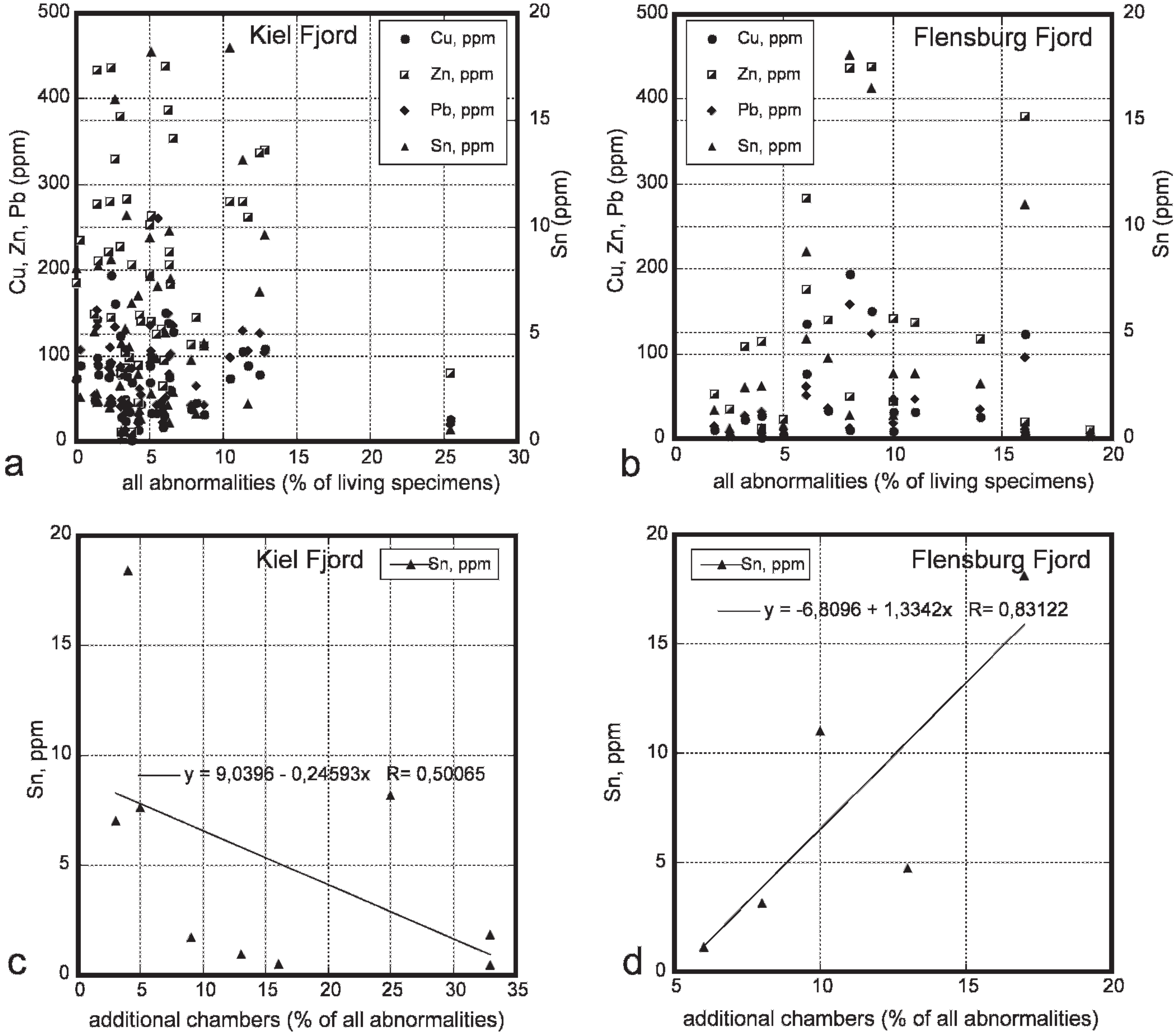

FIGURE 5. Relationships between test abnormalities and trace metal content of surface sediments from the Kiel (a, c) and Flensburg (b, d) Fjords.

and the major source for this metal in study area is organotin compounds from antifouling paints, it could be concluded that organotin is toxic, not only to mollusks (LANU, 2001), but also to foraminifera (Gustafsson and others, 2000).

In vertebrates, the majority of absorbed lead ends up in bones and teeth (Barry, 1975), and in foraminifera, it should be accumulated in the carbonate test. It was shown that heavy metals seem to induce a crystalline disorganization and formation of interlammelar cavities, leading to test abnormalities (Geslin and others, 1998). To test these hypotheses, we did EDS analysis of heavy metals in foraminiferal tests. However, there were no differences in metal content between normal and abnormal tests. Our results are contradictory to those of Samir and El Din (2001), who reported higher concentrations of Cu and Zn in abnormal specimens. This can be explained either by the lower resolution of the EDS analyzer or the shorter counting time that we used (57 s on average). However, Geslin and others (1998) also did not observe any differences in metal concentrations between normal and abnormal tests.

An increase in the proportion of abnormal tests from the western part of the Kiel Fjord to the Schwentine river mouth could either be related to the high input of organic matter with river run-off or to changes in salinity. The excessively spiroconvex tests of *Ammonia beccarii* were found in the inner, middle and outer parts of the river. Spiroconvex tests were reported as an indicator of high organic-matter content (Seiglie, 1975; Samir and El Din, 2001). On the other hand, variations from saline to freshwater conditions are apparently also unfavorable for benthic foraminifera (Wennrich and others, 2007). The river discharge and variable salinity in the Schwentine area

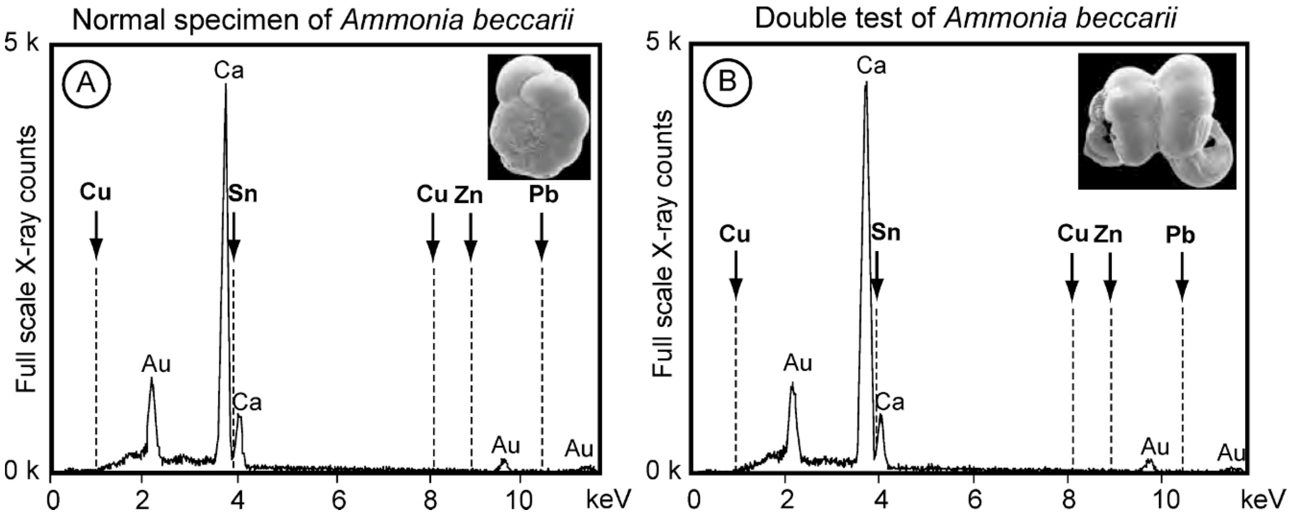

FIGURE 6. An example of results of EDS analysis, performed for **A** a normal test and **B** an abnormal test of *Ammonia beccarii*.

can thus also lead to an increased proportion of test abnormalities.

Excessively spiroconvex tests were also frequent in the inner (PF15-90) and central fjord (PF15-14; PF15-45) and off Heikendorf (PF15-79), where they coincided with high TOC content. An exception was site PF15-17, which had a low content of all organic compounds and heavy metals, yet had the highest proportion (25%) of total abnormal tests of all samples from the Kiel Fjord. Similar settings were observed in the Flensburg Fjord, where the occurrence of excessively spiroconvex tests (as the most dominant abnormality type in *Ammonia beccarii*) coincided with the lowest levels of organic compounds. However, those sampling sites with the highest proportions of abnormal tests are situated at the entrance of the Kiel and Flensburg fjords and can be thus influenced by the advection of higher-salinity deep water. Therefore, a high variability of salinity at such settings must be considered (Lutze, 1965, 1974).

Predominance of Small Test Abnormalities

In both fjords, a predominance of small test deformations, such as reduced and overdeveloped chambers, was observed. Myers (1943) reported reduced chamber size in foraminiferal tests and noted that chambers formed during the winter are often smaller than those added during the summer, thus leading to an irregular test shape. These circumstances could be valid for the Kiel Fjord, where samples containing foraminifera with reduced chambers were taken in winter. However, this argument does not account for the excessive number of small test abnormalities in Flensburg Fjord, where sampling took place in summer.

Nevertheless, small test deformations presumably do not reflect long-term environmental stress, and might only correspond to transient local disturbances in the environment (Geslin and others, 2000). As a predominance of small test abnormalities was observed at the entrance of both the Kiel and Flensburg Fjords, it appears that occasional salinity changes, due to saltwater intrusion from the Belt Sea, have a transient effect on test development.

Morphological Constraints for Development of Abnormal Tests

The results obtained in this study pose the question whether some test abnormalities are species specific. According to our findings, excessively spiroconvex tests and bulla-like chambers at the umbilicus are typical of only *Ammonia beccarii*. It might well be that, related to the peculiarities of test morphology, there are only limited possibilities for development of test abnormalities. Similar assumptions came from the moving reference model of foraminiferal tests development (Tyszka and others, 2005; Tyszka, 2006). These authors reported that tests develop in a normal way only in a certain morphophase. As applied to *A. beccarii*, by morphophase we mean the trochospiral morphology of its test. Once test development approaches a transitional area-for example, a distinct change from a trochospiral to a planispiral or irregular morphophase-even a slight change in parameters (deviation angle, rotation angle or chamber scaling rate) can lead to a radical change in test morphology (Tyszka, 2006). This morphological feature allows *Ammonia* spp. to develop the species-specific abnormality types, such as bulla-like chambers and excessively spiroconvex tests, which certainly do not occur in species with planispiral tests. The formation of species-specific types of test abnormality is therefore consistent with the concept of a "vacant range" (Tyszka, 2006) of a certain morphophase, which is therefore limited. As such, a species with trochospiral morphology has only limited possibilities for the development of different abnormality types.

Abnormal Tests of *Ammonia beccarii* in the Gelting Bay

Shell Loss

Buzas-Stephens and Buzas (2005) reported three possibilities for shell loss in living specimens: predation, abrasion and test dissolution. In the western Baltic Sea, abrasion and dissolution were considered responsible for shell loss (Grobe and Fütterer, 1981). Walker (1991) observed etched

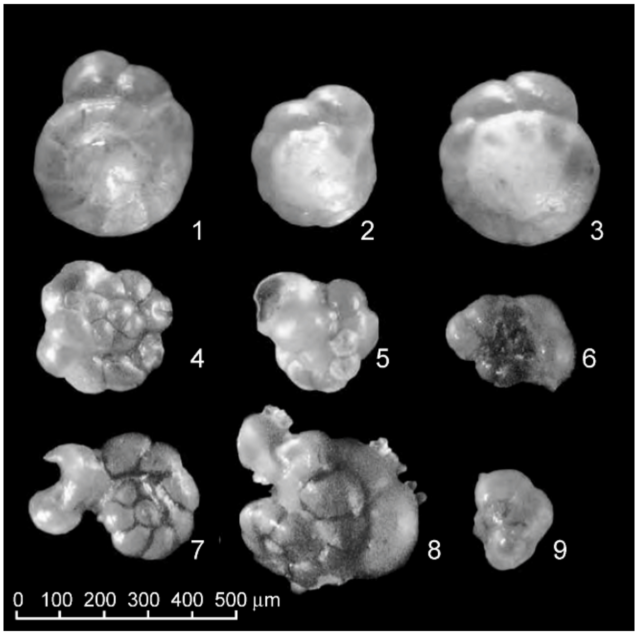

PLATE 4

Light micrographs of *Ammonia beccarii* tests from the Gelting Bay, the Flensburg Fjord: **1** Normal specimen, spiral view; **2, 3** Opaque tests, as the first stage of test dissolution; **4–6, 9** Double tests showing the smaller specimens exhibiting disruptions in the coiling plane; **7–8** Double tests with individuals firmly attached to the partially or fully destroyed bigger foraminifera.

foraminiferal tests after ingestion of foraminifera by the periwinkle *Littorina littorea*, which occurs in both fjords (Worm and Lotze, 2006). He noted that rotaliid specimens were still alive after having been ingested, subjected to the mechanical and chemical digestion, and removed from the gut or faecal pellets of the gastropod. This fact might explain why all corroded foraminiferal individuals we observed in the Gelting Bay were alive (stained). On the other hand, we found relatively high foraminiferal population densities (170 ind/10 cm^3 on average) in the sandy sediments of the Gelting Bay, in spite of low food availability (TOC - 0.4%, SiO_2 - 1%, Chl a - 11 mkg/g on average) as compared to the inner fjord (TOC - 11%, SiO_2 - 6%, Chl a - 108 mkg/g on average). Under similar conditions, Buzas and others (1989) did an experiment on predation and observed very low foraminiferal population densities (1.5 ind/10 cm^3 maximum). Therefore, if predation played a significant role in the shell loss, it would also affect the foraminiferal abundances, though they were quite high in our case.

Analysis of SEM images revealed that corroded specimens with visible inner organic linings (Pl. 3, Figs. 2–5) most likely result from test dissolution (E. Alve, written communication, 2007). A similar situation was observed at a pH ~ 7 in Sandebukta (Oslo Fjord) by Alve and Nagy (1986), who reported dissolved *Ammonia batavus* associated with seasonally enhanced dissolution of calcareous tests between April and June. In the southwestern Baltic Sea, similar dissolution processes driven by seasonality were described in the Eckernförde Bay, where foraminiferal tests dissolve in the uppermost millimeters of the sediment (Wefer, 1976).

Since the dissolution phenomenon was unknown to us at the time of sampling, no measurements of pH values in bottom and pore waters were conducted in the Flensburg Fjord, and we can only speculate that a lowering of pH could induce shell loss. In the majority of corroded foraminiferal tests, the last chambers were missing (Pl. 3, Figs. 2, 3). Le Cadre and others (2003) reported loss of the final and thinnest chambers as an initial stage of test dissolution at a pH of 7 during culture experiments.

Shell loss in the Flensburg Fjord occurs exclusively in tests of *Ammonia beccarii*; up to 100% of the *Ammonia* individuals we found were corroded. As it was shown by experimental studies for *Ammonia tepida* (Stouff and others, 1999b; Le Cadre and others, 2003; Le Cadre and Debenay, 2006), a specimen of this species is able to thicken its inner organic lining under unfavorable conditions and thus regenerate a damaged test. We observed the traces of such regeneration in individuals of *A. beccarii* from the Kiel Fjord (Pl. 1, Fig. 5). At the same time, *Ammonia* spp. have different modes of life: epifaunal, infaunal, epiphytic (Debenay and others, 1998; Murray, 2006). Therefore, an infaunal mode of life could

TABLE. 3. Correlations between abnormality types and environmental parameters in the Kiel and Flensburg Fjords. The significance test for a linear correlation for normally distributed data was performed according to Assmann and others (2007). Note the type I error at α=0.05. Bold numbers indicate the correlations, which passed a significance test (i.e., have a Student's t value higher than $t_{n-2,\ 1-\alpha}$).

Study area	Abnormality type	Geochemical parameters in sediments	Correlation coefficient (r)	Student's *t-test*, (t)	Quantile, ($t_{n-2,\ 1-\alpha}$)
Kiel Fjord	Additional chamber	Sn	−0.501 (n=10; p=0.2)	−1.706	1.812
	Wrong coiling	TOC	−**0.522** (n=9; p=0.1)	−2.026	1.895
	-	TN	−**0.578** (-)	−2.037	1.895
	-	Chl a	−**0.763** (n=9; p=0.01)	−3.848	1.895
Flensburg Fjord	Additional chamber	Cu	**0.886** (n=5; p=0.1)	3.619	2.35
	-	Zn	**0.857** (-)	2.986	2.35
	-	Sn	**0.831** (-)	2.795	2.35
	-	Pb	**0.847** (-)	2.932	2.35
	-	TN	−0.627 (n=6; p=0.2)	1.605	2.132
	Twisting of entire test	Cu	0.596 (-)	1.610	2.132
	-	Zn	0.541 (n=6; p=0.3)	1.366	2.132
	-	Sn	0.603 (n=6; p=0.2)	1.560	2.132
	-	Pb	0.697 (n=6; p=0.1)	2.075	2.132

Bold numbers indicate significant correlations, which passed Student's *t-test*.
"-" means the same as above.

also be responsible for shell loss in that the changes in pH are more profound in the pore waters.

Another possible reason for shell loss is eutrophication, which lowers oxygen levels and makes pore waters anoxic and sulfidic (Jorissen, 1999) affecting dissolution processes. However, we did not observe high levels of organic matter in the Gelting Bay, as compared to the inner Flensburg Fjord (see above). In addition, sandy sediments in this area do not facilitate the accumulation of heavy metals and organic matter. Thus, we can exclude eutrophication from the reasons inducing shell loss in the Gelting Bay.

Exon (1971) reported that the eastern Gelting Bay is an area exposed to intensive bottom currents of 30 cm/s that cause active westward long-shore sediment drift. Transport of such strong currents can damage living benthic foraminiferal tests, causing abnormal test shapes to form during the regeneration of damaged chambers (Geslin and others, 2002). Nevertheless, some corroded shells of *Ammonia beccarii* had only interlocular walls. These so-called star-shaped tests (Pl. 3, Fig. 5) have been reported after heavy dissolution (Buzas-Stephens and Buzas, 2005; Le Cadre and others, 2003). This peculiar test shape is easily distinguishable from the shell breaks caused by abrasion, which also destroys interlocular walls. We therefore conclude that dissolution is the main process responsible for the shell loss seen in the Flensburg Fjord.

Multiple Tests

A sample, taken off the Gelting Noor showed a distinct abnormality type in *Ammonia beccarii* resembling a fusion of two specimens. A smaller individual displayed extremely thin walls and disruptions in the coiling plane. The bigger specimen had thick but corroded walls, creating an illusion sometimes of a new foraminifer emerging from the older, corroded test. From Southampton Water (UK), Sharifi and others (1991) reported similar double specimens, which also differed in size. These authors noted that double specimens of the same size are very rare.

Culture experiments under hypersaline conditions (Stouff and others, 1999a, b) revealed the following reasons for double or multiple tests. Firstly, an anomaly in the development of a single juvenile can cause the formation of double tests. In this case, two protuberances can form on the uncalcified proloculus of a young specimen, leading to the formation of two second chambers with subsequent development of whorls from each of the second chambers. Secondly, multiple tests result from an early fusion of two young specimens which both continue their development. Finally, attachment of the juvenile to a parental test can occur after schizogony. After fusion, the attached juvenile continues its development creating thus a double test.

On the other hand, Wennrich and others (2007) suggested the formation of double tests is caused by hyposalinity. The area off the Gelting Noor faces the saltwater inflows from the Danish Straits (Exon, 1971). Foraminifera dwelling in the Gelting Bay can undergo drastic and sudden changes in salinity. If the timing of saltwater intrusion coincides with periods of foraminiferal reproduction, abrupt salinity changes might prevent

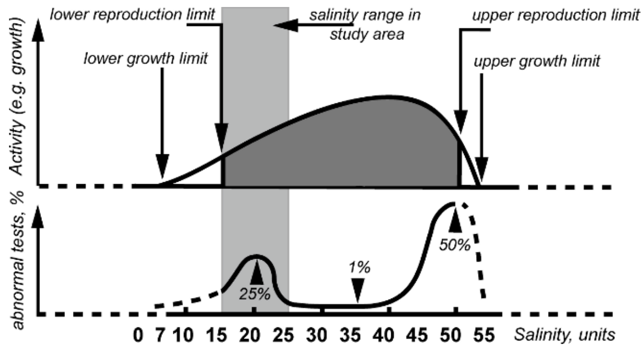

FIGURE 7. Conceptual model, illustrating the salinity tolerance curve of representatives of the genus *Ammonia* and salinity range for development of abnormal tests. According to this model, the lower reproduction and growth limits correspond to the findings of Bradshaw (1957, 1961), who did not observe any reproduction activity of *Ammonia beccarii* at 40 psu. The upper reproduction limit is based on the culture observations of Stouff and others (1999b). The upper growth limit was suggested by the observations of Almogi-Labin and others (1992), who reported abnormal tests (17%) of living *A. beccarii* in a hypersaline pool (Dead Sea) at 55 psu. Maximal frequency of test abnormalities (50%) is according to findings of Stouff and others (1999b). One percent represents a reference proportion of abnormal tests within a natural, undisturbed population, whereas 25% is a maximal frequency of abnormalities recorded in this study within a salinity range of 15–25 psu in the southwestern Baltic Sea.

dispersal and facilitate the early fusion of juveniles after schizogony (Stouff and others, 1999a, b), leading to the formation of abnormal tests.

ABNORMALITIES CAUSED BY ABRUPT SALINITY CHANGES

Ammonia beccarii was described by Wefer (1976) as an euryhaline species that ranges from hypo- to hypersalinities. This species provides the majority of specimens with abnormal tests at the sites affected by salt-water intrusion in both fjords. In addition, the spatial distribution of all groups of abnormalities in both fjords points to the higher frequencies in areas with salinity variations, and namely the outer parts of the Gelting Bay and the Schwentine river mouth. Therefore, we suggest that critical thresholds of salinity induce the development of foraminiferal test abnormalities. Based on our findings and previous studies (see caption to Fig. 7), we propose a conceptual model illustrating the relationship between the normal development of representatives of the genus *Ammonia* and formation of abnormal tests (Fig. 7).

Our results confirm the hypothesis that hyposalinity can be responsible for development of abnormal tests. Even if the observed salinity range is within the tolerance of a certain species, salinity levels close to the lower reproduction limit (Fig. 7) might induce the formation of aberrant tests, owing to the enhanced vulnerability of the juvenile specimens. The salinity needs only to rise or fall suddenly, as happens often in the western Baltic Sea, to facilitate the formation of abnormal tests.

The overwhelming majority of specimens found in the current study was megalospheric and represented therefore the offspring produced asexually (Alve and Goldstein, 2003). Megalospheric tests prevail in most natural populations (Leutenegger, 1977; Lehmann and others, 2006) and often indicate that the asexual reproduction mode is more appropriate under unfavorable conditions (Nigam and Caron, 2000; Coccioni, 2000). Vice versa, a culture experiment with *Rosalina leei* showed that an increase in temperature resulted in an increase in tendency for sexual reproduction (Nigam and Caron, 2000). In our case, a predominance of offspring produced asexually might thus reflect the inflow of more cold and salt-rich bottom water from the Belt Sea. Elevated frequencies of abnormalities might indicate a population surviving highly variable environmental conditions close to the species' reproduction limit.

CONCLUSIONS

We recognized 18 types of foraminiferal test abnormalities in the Kiel and Flensburg Fjords of the Kiel Bay. According to morphological criteria, the types were classified into five groups: chamber, apertural, umbilical, coiling and test abnormalities. In both fjords, a predominance of small test deformities, such as reduced and overdeveloped chambers, was observed. These small test deformations are here related to short-term environmental changes. In particular, intrusions of salt-rich bottom waters from the Belt Sea are the cause of the highest proportions of abnormal foraminiferal tests in the outer parts of both fjords. In the inner fjords, elevated levels of heavy metals apparently lead to high percentages of abnormal tests. Our data show a different relationship between abnormal tests and heavy metals in the two fjords due to different hydrographical conditions.

In both fjords, test abnormalities are over-represented in *Ammonia beccarii* and under-represented in *Elphidium excavatum* subspecies compared to their average proportions in the living assemblages. A bulla-like chamber covering the umbilicus and excessively spiroconvex tests were seen only in *A. beccarii*. These species-specific abnormalities were explained by the limited possibilities for abnormal development due to the trochospiral morphology of *Ammonia* spp.

Tests of *Ammonia beccarii* found in the Flensburg Fjord showed distinct irregularities reflecting dissolution and development of double tests due to special environmental conditions in the Gelting Bay, where changes in salinity and enhanced sediment redeposition prevail. Our study confirms the hypothesis that within a certain area, natural instability might be more important than anthropogenic influence for development of abnormal tests. Even if environmental variability is well within the range of tolerance of a given species, such environmental changes might cause abnormalities if coincident with a period of high sensitivity of the organisms (e.g., during reproduction). Thus, using abnormal foraminiferal tests as an indicator of environmental pollution must be done with care, especially in settings exhibiting unstable environmental conditions.

ACKNOWLEDGMENTS

The authors are grateful to crew of RV *Polarfuchs* Holger *Meyer* and Helmut Schramm for help with sampling. We are indebted to Anna Nikulina, who provided the data on sediment geochemistry and helped with foraminiferal analysis of samples. We acknowledge Udo Laurer (IFM-GEOMAR), Ute Schuldt (Institute of Geosciences, Kiel) and Irina Gembitskaya (St. Petersburg State Mining Institute) for technical assistance. We also wish to thank Rodolfo Coccioni (University of Urbino), anonymous reviewer, Charlotte Brunner (University of Southern Mississippi) and Pamela Hallock (University of South Florida) for constructive comments, valuable suggestions and reviewing of this manuscript. Our sincere thanks go to Elisabeth Alve (University of Oslo) for her valuable advice during the early stage of this study. Finally, we want to express our gratitude to Brian Haley (IFM-GEOMAR) for linguistic corrections of an earlier version of this manuscript. This study was funded by Leibniz Award DFG DU 129-33 and by a research grant of the Otto-Schmidt Laboratory (AARI, St. Petersburg).

REFERENCES

ABU-HILAL, A. H., and BADRAN, M. M., 1990, Effect of pollution sources on metal concentration in sediment cores from the Gulf of Aqaba (Red Sea): Marine Pollution Bulletin, v. 21, p. 190–197.

ALMOGI-LABIN, A., PERELIS-GROSSOVICZ, L., and RAAB, M., 1992, Living *Ammonia* from a hypersaline inland pool, Dead Sea area, Israel: Journal of Foraminiferal Research, v. 22, p. 257–266.

ALLOWAY, B. J., 2005, Bioavailability of elements in soil, *in* Sellinus, O., Alloway, B. J., Centeno, J. A., Finkelman, R. B., Fuge, R., Lindh, U., and Smedley, P. (eds.), Medical Geology: Impacts of the Natural Environment on Public Health: Elsevier, San Diego, p. 347–372.

ALVE, E., 1991, Benthic foraminifera in sediment cores reflecting heavy metal pollution in Soerfjord, Western Norway: Journal of Foraminiferal Research, v. 21, p. 1–19.

———, and NAGY, J., 1986, Estuarine foraminiferal distribution in Sandebukta, a branch of the Oslo Fjord: Journal of Foraminiferal Research, v. 16, p. 261–284.

———, and GOLDSTEIN, S., 2003, Propagule transport as a key method of dispersal in benthic foraminifera (Protista): Limnology and Oceanography, v. 48, p. 2163–2170.

ANKLEY, G. T., THOMAS, N. A., DI TORO, D. M., HANSEN, D. J., MAHONY, J. D., BERRY, W. J., SWARTZ, R. C., HOKE, R. A., GARRISON, A. W., ALLEN, H. E., and ZARBA, C. S., 1994, Assessing potential bioavailability of metals in sediments: a proposed approach: Environmental Management, v. 18, p. 331–337.

ASSMANN, C., GOLOSNOY, V., and HOGREFE, J., 2007, Formelsammlung zur Methodenlehre der Statistik II, beta – version: Institut fr Statistik und Ökonometrie der Christian-Albrechts-University Kiel, Kiel, Germany, 63 p.

BARRY, P. S. I., 1975, Lead levels in blood: Letters to Nature, v. 258, p. 775.

BELLINGER, E. G., and BENHAM, B. R., 1978, The levels of metals in dock-yard sediments with particular reference to the contributions from ship-bottom paints: Environmental Pollution, v. 15, p. 71–81.

BERGIN, F., KUCUKSEZGIN, F., ULUTURHAN, E., BARUT, I. F., MERIC, E., AVSAR, N., and NAZIK, A., 2006, The response of benthic foraminifera and ostracoda to heavy metal pollution in Gulf of Izmir (Eastern Aegean Sea): Estuarine Coastal and Shelf Science, v. 66, p. 368–386.

BOLTOVSKOY, E., and WRIGHT, R., 1976, Recent Foraminifera: W. Junk, The Hague, 515 p.

———, SCOTT, D. B., and MEDIOLI, F. S., 1991, Morphological variations of benthic foraminiferal tests in response to changes in ecological parameters: a review: Journal of Paleontology, v. 65, p. 175–185.

BRADSHAW, J., 1957, Laboratory studies on the rate of growth of the foraminifer "*Streblus beccarri* (Linne) var. *tepida* (Cushman)": Journal of Paleontology, v. 31, p. 1138–1147.

———, 1961, Laboratory experiments on the ecology of foraminifera: Contributions from the Cushman Foundation for Foraminiferal Research, v. 7, no. 3, p. 87–106.

Burone, L., Venturini, N., Sprechmann, P., Valente, P., and Muniz, P., 2006, Foraminiferal responses to polluted sediments in the Montevideo coastal zone, Uruguay: Marine Pollution Bulletin, v. 52, p. 61–73.

Buzas, M. A., Collins, L. S., Richardson, S. L., and Severin, K. P., 1989, Experiments on predation, substrate preference, and colonization of benthic foraminifera at the shelf break off the Ft. Pierce Inlet, Florida: Journal of Foraminiferal Research, v. 19, p. 146–152.

Buzas-Stephens, P., and Buzas, M. A., 2005, Population dynamics and dissolution of Foraminifera in Nuices Bay, Texas: Journal of Foraminiferal Research, v. 35, p. 248–258.

Chester, R., and Aston, R., 1976, The geochemistry of deep-sea sediments, *in* Riley, J. P., and Chester, R. (eds.), Chemical Oceanography, v. 6: Academic Press, London, p. 281–390.

Clark, E. A., Sterritt, R. M., and Lester, J. N., 1988, The fate of tributyltin in the aquatic environment: a look at the data: Environmental Science and Technology, v. 22, p. 600–604.

Coccioni, R., 2000, Benthic foraminifera as bioindicators of heavy metal pollution, *in* Martin, R. M. (ed.), Environmental Micropaleontology: The Application of Microfossils to Environmental Geology: Kluwer Academic Publishers/Plenum Publishers, New York, p. 71–103.

Debenay, J.-P., Beneteau, E., Zhang, J., Stouff, V., Geslin, E., Redois, F., and Fernandez-Gonzalez, M., 1998, *Ammonia beccarii* and *Ammonia tepida* (Foraminifera): morphofunctional arguments for their distinction: Marine Micropaleontology, v. 34, no. 3–4, p. 235–244.

De Nooijer, L., 2007, Shallow-water Benthic Foraminifera as Proxy for Natural Versus Human-induced Environmental Change: Geologica Ultraiectina, Mededelingen van de Faculteit Geowetenschappen Universiteit Utrecht, Netherlands, v. 272, 152 p.

Di Leonardo, R., Bellanca, A., Capotondi, L., Cundy, A., and Neri, R., 2007, Possible impacts of Hg and PAH contamination on benthic foraminiferal assemblages: an example from the Sicilian coast, central Mediterranean: Science of the Total Environment, v. 388, p. 168–183.

Erlenkeuser, H., Suess, E., and Willkomm, H., 1974, Industrialisation affects heavy metal and carbon isotope concentrations in recent Baltic Sea sediments: Geochimica et Cosmochimica Acta, v. 38, p. 823–842.

Ernst, S. R., Morvan, J., Geslin, E., Le Bihan, A., and Jorissen, F. J., 2006, Benthic foraminiferal response to experimentally induced Erika oil pollution: Marine Micropaleontology, v. 61, p. 76–93.

Exon, N., 1971, Holocene sedimentation in and near the outer Flensburg Fjord (westernmost Baltic Sea): Ph.D. Thesis, Christian-Albrechts-University, Kiel, Germany, 102 p.

———, 1972, Sedimentation in the outer Flensburg Fjord area (Baltic Sea) since the last Glaciation: Meyniana, v. 22, p. 5–62.

Fennel, W., 1996, Wasserhaushalt und Strömung, *in* Rheinheimer, G. (ed.), Meereskunde der Ostsee: Springer Verlag, Berlin, p. 56–67.

Förstner, U., 1993, Metal speciation–general concept and application: International Journal of Environmental Analytical Chemistry, v. 51, p. 5–23.

Frenzel, P., Tech, T., and Bartholdy, J., 2005, Checklist and annotated bibliography of Recent Foraminiferida from the German Baltic Sea coast, *in* Tyszka, J. (ed.), Methods and Applications in Micropaleontology: Studia Geologica Polonica, v. 124, p. 67–86.

Frontalini, F., and Coccioni, R., 2008, Benthic foraminifera for heavy metal pollution monitoring: a case study from the central Adriatic Sea coast of Italy: Estuarine Coastal and Shelf Science, v. 76, p. 404–427, doi:10.1016/j.ecss.2007.07.024

Gemeinsames Komitee Flensburger Förde, 1974, Untersuchungen der Flensburger Förde: Wasseraustausch, Teilbericht 7: Selbstverlag, Amtshuset, Aabenraa, 129 p.

Geslin, E., Debenay, J.-P., and Lesourd, M., 1998, Abnormal wall textures and test deformation in *Ammonia* (hyaline foraminifer): Journal of Foraminiferal Research, v. 28, p. 148–156.

———, Stouff, V., Debenay, J.-P., and Lesourd, M., 2000, Environmental variation and foraminiferal test abnormalities, *in* Martin, R. M. (ed.), Environmental Micropaleontology: The Application of Microfossils to Environmental Geology: Kluwer Academic Publishers/Plenum Publishers, New York, p. 191–215.

———, Debenay, J.-P., Duleba, W., and Bonetti, C., 2002, Morphological abnormalities of foraminiferal tests in Brazilian environments: comparison between polluted and non-polluted areas: Marine Micropaleontology, v. 45, p. 151–168.

Grobe, H., and Fütterer, D., 1981, Zur Fragmentierung benthischer Foraminiferen in der Kieler Bucht (Westliche Ostsee): Meyniana, v. 33, p. 85–96.

Gustafsson, M., Dahllöf, I., Blanck, H., Hall, P., Molander, S., and Nordberg, K., 2000, Tri-n-butyltin (TBT) pollution in an experimental mesocosm: Marine Pollution Bulletin, v. 40, p. 1072–1075.

Hayward, B. W., Holzmann, M., Grenfell, H. R., Pawlowski, J., and Triggs, C. M., 2004, Morphological distinction of molecular types in *Ammonia*-towards a taxonomic revision of the world's most commonly misidentified foraminifera: Marine Micropaleontology, v. 50, p. 237–271.

Helland, A., and Bakke, T., 2002, Transport and sedimentation of Cu in microtidal estuary, SE Norway: Marine Pollution Bulletin, v. 44, p. 149–155.

Jorissen, F. J., 1999, Benthic foraminiferal microhabitats below the sediment-water interface, *in* Sen Gupta, B. K. (ed.), Modern Foraminifera: Kluwer Academic Publishers, Dordrecht, p. 161–179.

LANU, 2001, Organozinnverbindungen in Hafensedimenten und biologische Effekte, Untersuchungen in Sedimenten und an der Strandschnecke (Littorina littorea L.) in schleswig-holsteinischen Küstengewässern. Landesamt für Natur und Umwelt des Landes Schleswig-Holstein, Open Rep., 55 p. http://www.lanu.landsh.de.

LANU, 2007, Sauerstoffmangel im bodennahen Wasser der westlichen Ostsee im September 2007, MURSYS Ostsee, Landesamt für Natur und Umwelt des Landes Schleswig-Holsteins, Flintbek, http://www.bsh.de/de/Meeresdaten/Beobachtungen/MURSYS-Umweltreportsystem/Mursys_031/seiten/oso27_01.jsp#september2007.

Le Cadre, V., and Debenay, J.-P., 2006, Morphological and cytological responses of *Ammonia* (foraminifera) to copper contamination: implication for the use of foraminifera as bioindicators of pollution: Environmental Pollution, v. 143, p. 304–317.

———, Debenay, J.-P., and Lesourd, M., 2003, Low pH effects on *Ammonia beccarii* test deformation: implications for using test deformations as a pollution indicator: Journal of Foraminiferal Research, v. 33, p. 1–9.

Lehmann, G., Röttger, R., and Hohenegger, J., 2006, Life cycle variation including trimorphism in the foraminifer *Trochammina inflata* from North European salt marshes: Journal of Foraminiferal Research, v. 36, p. 279–290.

Leutenegger, S., 1977, Reproductive cycles of larger foraminifera and depth distributions of generations: Utrecht Micropaleontological Bulletin, v. 15, p. 26–34.

Lutze, G.-F., 1965, Zur Foraminiferen-Fauna der Ostsee: Meyniana, v. 15, p. 75–142.

———, 1974, Foraminiferen der Kieler Bucht (Westliche Ostsee): 1. «Hausgartengebiet» des Sonderforschungsbereiches 95 der Universität Kiel: Meyniana, v. 26, p. 9–22.

Mantoura, R. F. C., Dickson, A., and Riley, J. P., 1978, The complexation of metals and humic materials in natural waters: Estuarine and Coastal Marine Sciences, v. 6, p. 387–408.

Mikhalevich, V. I., 1976, New data on the foraminifera of the groundwaters of Middle Asia: International Journal of Speleology, v. 8, p. 167–175.

Miller, A. A. L., Scott, D. B., and Medioli, F., 1982, *Elphidium excavatum* (Terquem): ecophenotypic versus subspecific variation: Journal of Foraminiferal Research, v. 12, p. 116–144.

Murray, J. W., 1963, Ecological experiments on Foraminiferida: Journal of the Marine Biological Association of the UK, v. 43, p. 621–642.

———, 2006, Ecology and Application of Benthic Foraminifera: Cambridge University Press, Cambridge, 438 p.

———, and Bowser, S., 2000, Mortality, protoplasm decay rate, and reliability of staining techniques to recognize "living" foraminifera: a review: Journal of Foraminiferal Research, v. 30, p. 66–70.

MYERS, E. H., 1943, Life activities of Foraminifera in relation to marine ecology: American Philosophical Society, Proceedings, v. 86, p. 439–458.

NIKULINA, A., POLOVODOVA, I., and SCHÖNFELD, J., 2007, Foraminiferal response to environmental changes in Kiel Fjord, SW Baltic Sea: Earth Discussions, v. 2, p. 191–217.

NIGAM, R., and CARON, D. A., 2000, Does temperature affects dimorphic reproduction in benthic foraminifera? A culture experiment on *Rosalina leei*: Current Science, v. 79, p. 1105–1106.

———, SARASWAT, R., and PANCHANG, R., 2006, Application of foraminifers in ecotoxicology: retrospect, perspect and prospect: Environmental International, v. 32, p. 273–283.

REEDER, R. J., SCHOONEN, M. A. A., and LANZIROTTI, A., 2006, Metal speciation and its role in bioaccessibility and bioavailability: Reviews in Mineralogy and Geochemistry, v. 64, p. 59–113.

RIIA (ROYAL INSTITUTE OF INTERNATIONAL AFFAIRS), 1990, Chronology and Index of the Second World War 1938–1945: Westport, London, 450 p. http://www.questiaschool.com/read/90208730?title=1944.

RÜDEL, H., 2003, Case study: bioavailability of tin and tin compounds: Ecotoxicology and Environmental Safety, v. 56, p. 180–189.

SAMIR, A. M., and EL-DIN, A. B., 2001, Benthic foraminiferal assemblages and morphological abnormalities as pollution proxies in two Egyptian bays: Marine Micropaleontology, v. 41, p. 193–127.

SARASWAT, R., KURTARKAR, S. R., MAZUMDER, A., and NIGAM, R., 2004, Foraminifers as indicators of marine pollution: a culture experiment with *Rosalina leei*: Marine Pollution Bulletin, v. 48, p. 91–96.

SCHWARZER, K., and THEMANN, S., 2003, Sediment distribution and geological buildup of Kiel Fjord (Western Baltic Sea): Meyniana, v. 55, p. 91–115.

SEIGLIE, G. A., 1975, Foraminifers of Guayanilla Bay and their use as environmental indicators: Revista Espanola de Micropaleontologia, v. 7, p. 453–487.

SEVERIN, K. P., 1990, Heterogeneous trace element distribution in foraminiferal tests: what paleoceanographic resolution can be achieved? Geological Society of America, Program with Abstracts, v. 22, p. 62.

SHARIFI, A. R., CROUDACE, L. W., and AUSTIN, R. L., 1991, Benthic foraminiferids as pollution indicators in Southampton Water, southern England, United Kingdom: Journal of Micropalaeontology, v. 10, p. 109–113.

SIEGEL, F. R., 2002, Environmental geochemistry of potentially toxic metals: Springer-Verlag, Berlin, 218 p.

STOUFF, V., DEBENAY, J.-P., and LESOURD, M., 1999a, Origin of double and multiple tests in benthic foraminifera: observations in laboratory cultures: Marine Micropaleontology, v. 36, p. 189–204.

———, GESLIN, E., DEBENAY, J.-P., and LESOURD, M., 1999b, Origin of morphological abnormalities in *Ammonia* (Foraminifera): studies in laboratory and natural environments: Journal of Foraminiferal Research, v. 29, p. 152–170.

———, LESOURD, M., and DEBENAY, J.-P., 1999c, Laboratory observations on asexual reproduction (schizogony) and ontogeny of *Ammonia tepida* with comments on the life cycle: Journal of Foraminiferal Research, v. 29, p. 75–84.

TESSIER, A., and CAMPBELL, P. G. C., 1987, Partitioning of trace metals in sediments: relationships with bioavailability: Hydrobiologia, v. 149, p. 43–52.

THEMANN, S., 2002, Quartärgeologischer Aufbau und Sedimentverteilung in der Kieler Förde: Diplom Arbeit, Institut für Geowissenschaften, Universität Kiel, 135 p.

TYSZKA, J., 2006, Morphospace of foraminiferal shells: results from the moving reference model: Lethaia, v. 39, p. 1–12.

———, TOPA, P., and SACZKA, K., 2005, State-of-the-art in modelling of foraminiferal shells: searching for an emergent model: Studia Geologica Polonica, v. 124, p. 143–157.

V.-BALOGH, K., 1988, Heavy metal pollution from a point source demonstrated by mussel (*Unio pictorium L.*) at Lake Balaton, Hungary: Bulletin of Environmental Contamination and Toxicology, v. 41, p. 910–914.

WAHL, M., 1985, The recolonization potential of *Metridium senile* in an area previously depopulated by oxygen deficiency: Oecologia, v. 67, p. 255–259.

WALKER, D. A., 1991, Etching of the test surface of benthonic foraminifers due to ingestion by the gastropod *Littorina littorea* Linne: Canadian Journal of Earth Science, v. 8, p. 1487–1491.

WATKINS, J. G., 1961, Foraminiferal ecology around the Orange County, California, ocean sewer outfall: Micropaleontology, v. 7, no. 2, p. 199–206.

WEDEPOHL, K. H., 1960, Spurenanalytische Untersuchungen an Tiefseetonen aus dem Atlantik: Ein Beitrag zur Deutung der geochemischen Sonderstellung von pelagischen Tonen: Geochimica et Cosmochimica Acta, v. 18, p. 200–231 [in German with an English abstract].

WEFER, G., 1976, Umwelt, Produktion und Sedimentation benthischer Foraminiferen in der westlichen Ostsee: Reports Sonderforschungsbereich 95 Wechselwirkung Meer-Meeresboden, v. 14, p. 1–103.

WENNRICH, V., MENG, S., and SCHMIEDL, G., 2007, Foraminifers from Holocene sediments of two inland brackish lakes in central Germany: Journal of Foraminiferal Research, v. 37, p. 318–326.

WORM, B., and LOTZE, H. K., 2006, Effects of eutrophication, grazing, and algal blooms on rocky shores: Limnology and Oceanography, v. 51, p. 569–579.

YANKO, V., KRONFELD, A., and FLEXER, A., 1994, The response of benthic foraminifera to various pollution sources: implications for pollution monitoring: Journal of Foraminiferal Research, v. 24, p. 1–17.

———, AHMAD, M., and KAMINSKI, M., 1998, Morphological deformities of benthic foraminiferal tests in response to pollution by heavy metals: implication for pollution monitoring: Journal of Foraminiferal Research, v. 28, p. 177–200.

———, ARNOLD, A. J., and PARKER, W. C., 1999, Effects of marine pollution on benthic Foraminifera, *in* Sen Gupta, B. K. (ed.), Modern Foraminifera: Kluwer Academic Publishers, Dordrecht, p. 217–235.

Received 29 February 2008
Accepted 30 June 2008

APPENDIX 1

List of species mentioned in this paper

Ammonia beccarii (Linné) = *Nautilus beccarii* Linné, 1758; Schönfeld and Numberger, 2007a, p. 52, Pl. 1, fig. 2. (Note: *Ammonia tepida*; De Nooijer, 2007, p. 24, Pl. 1, fig. A; molecular types of *Ammonia* T1 and T2, Hayward and others, 2004, p. 256–258, Pl. II–IV).

Ammotium cassis (Parker) = *Lituola cassis* Parker, 1870; Frenzel and others, 2005, p. 75, fig. 4, no. 3.

Elphidium albiumbilicatum (Weiss) = *Nonion pauciloculum* Cushman subsp. *albiumbilicatum* Weiss, 1954; Frenzel and others, 2005, p. 73, fig. 2., no. 10; Schönfeld and Numberger, 2007a, p. 52, Pl. 1, fig. 4. [Note: *Elphidium asklundi* Brotzen, 1943 of Lutze (1965); *Cribroelphidium albiumbilicatum* of Frenzel (2005)].

Elphidium excavatum excavatum (Terquem) = *Polystomella excavata* Terquem, 1875, Miller and others, 1982, p. 127, Pl. 1, fig. 11–12; Schönfeld and Numberger, 2007a, p. 52, Pl. 1, fig.12–13.

Elphidium excavatum clavatum (Cushman), 1930; Miller and others, 1982, p. 127, Pl. 1, fig. 8; Schönfeld and Numberger, 2007a, p. 52, Pl. 1, fig. 7–9.

Elphidium gerthi van Voorthuysen, 1957; Lutze, 1965, p. 159, Pl. 15, fig. 45 (Note: *Cribrononion* cf. *gerthi* of author).

Elphidium incertum (Williamson) = *Polystomella umbilicatula* (Walker) var. *incerta* Williamson, 1858; Schönfeld and Numberger, 2007a, p. 52, Pl. 1, fig. 5–6.

Elphidium williamsoni Haynes, 1973; Frenzel and others, 2005, p. 73, fig. 2., No. 8. [Note: *Cribrononion* cf. *alvarezianum Orbigny*, 1839 of Lutze (1965); *Cribroelphidium williamsoni* of Frenzel (2005)].

APPENDIX 2

Station list. Temperature, salinity and oxygen content are given for near-bottom waters, whereas sand content (fraction >63 µm) indicates sediment type. The table can be found on the Cushman Foundation website in the JFR Article Data Repository (http://www.cushmanfoundation.org/jfr/index.html) as item number JFR_DR200806.

APPENDIX 3

Geochemical data for samples taken in the Kiel Fjord. The table can be found on the Cushman Foundation website in the JFR Article Data Repository (http://www.cushmanfoundation.org/jfr/index.html) as item number JFR_DR200806.

APPENDIX 4

Foraminiferal census data. The table can be found on the Cushman Foundation website in the JFR Article Data Repository (http://www.cushmanfoundation.org/jfr/index.html) as item number JFR_DR200806.